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SURFACE WATER QUALITY

Changes in Water Quality of Grand Lake St. Marys Watershed Following Implementation of a Distressed Watershed Rules Package

Stephen J. Jacquemin,* Laura T. Johnson, Theresa A. Dirksen, and Greg McGlinch

Abstract

Grand Lake St. Marys watershed has drawn attention over the past decade as water quality issues resulting from nutrient loading have come to the forefront of public opinion, political concern, and scientific study. The objective of this study was to assess long-term changes in water quality (nutrient and sediment concentrations) following the distressed watershed rules package instituted in 2011. Since that time, a variety of rules (e.g., winter manure ban) and best management practices (cover crops, manure storage or transfers, buffers, etc.) have been implemented. We used a general linear model to assess variation in total suspended solids, particulate phosphorus, soluble reactive phosphorus (SRP), nitrate N, and total Kjeldahl nitrogen concentrations from daily Chickasaw Creek (drains ~25% of watershed) samples spanning 2008 to 2016. Parameters were related to flow (higher values during high flows), timing (lower values during winter months), and the implementation of the distressed watershed rules package (lower values following implementation). Overall, reductions following the distressed designation for all parameters ranged from 5 to 35% during medium and high flow periods (with exception of SRP). Reductions were even more pronounced during winter months covered by the manure ban, where all parameters (including SRP) exhibited decreases at medium and high flows between 20 and 60%. While the reductions seen in this study are significant, concentrations are still highly elevated and continue to be a problem. We are optimistic that this study will serve to inform future management in the region and elsewhere.

Core Ideas

- Grand Lake St. Marys receives high nutrient runoff from crop and livestock agriculture.
- The watershed was declared distressed in 2011, and management priorities were implemented.
- Management priorities included a winter manure application ban and encouraged other BMPs.
- Reductions in TSS, PP, SRP, NO_3^-, and TKN were noted at all flows following the designation.
- This represents an important step toward improved water quality in the watershed.

Grand Lake St. Marys (GLSM) watershed in Ohio has drawn a considerable amount of attention over the past decade at both the local and regional levels as water quality issues therein have come to the forefront of public opinion, political concern, and scientific study. Similar to many other hypereutrophic systems, the degraded water quality has been linked to agricultural runoff. While agricultural runoff is not unique to GLSM, the high percentage of row-crop and livestock production in the region (approximately 80–90% agricultural) that drains into smaller tributaries (first to second order) and ultimately feeds a single shallow (~1.5-m) and expansive (~15-km) basin builds nutrient levels quickly and exacerbates eutrophication to a high degree (Filbrun et al., 2013; GLWWA, 2008; Hoorman et al., 2008). Assessments in the mid-2000s characterized the majority of GLSM tributaries as well as the lake itself as ranking in the 90th percentile for total nitrogen (N) and phosphorus (P) concentrations (Ohio EPA, 2007; USEPA, 2009; Dubrovsky and Hamilton, 2010). During this time, after years of anecdotal observations of degraded water quality, a tipping point in the watershed was formally noted whereby external and internal loadings were identified as catalysts for increasingly frequent harmful algal blooms (99th nationwide percentile for total microcystins; USEPA, 2009). These shifts in water quality resulted in designation changes by the state of Ohio, including periodic "no contact" warnings as well as a watershed-wide "distressed" label.

Since the distressed watershed designation in 2011, a series of obligatory and voluntary efforts to mitigate runoff have been undertaken. Given the concentration of livestock producers in the region, the primary source of nutrient runoff is from manure based fertilizers (GLWWA, 2008). Thus, the management and conservation focus has been aimed at reducing this type of nonpoint runoff. Following the distressed designation, livestock producers were required to have a nutrient management plan and adhere to the USDA NRCS Code 590 Nutrient Management standards when applying manure. Before this period, <25%

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Abbreviations: BDL, below detection limit; BMP, best management practice; EQIP, Environmental Quality Incentives Program; FWMC, flow weighted mean concentration; GLM, general linear model; GLSM, Grand Lake St. Marys; NCWQR, National Center for Water Quality Research; PP, particulate phosphorus; SRP, soluble reactive phosphorus; TKN, total Kjeldahl nitrogen; STP, soil test P; TMDL, total maximum daily load; TP, total phosphorus; TSS, total suspended solids.

of producers maintained an active nutrient management plan compared with >95% following the designation (Mescher and Springer, 2013). In addition, Ohio Administrative Code 901:13-1-11, Land Application of Animal Manure (phased in 2011–2013), implemented a manure application ban between 15 December and 1 March (or any period with frozen ground) of all subsequent years. Furthermore, while not specifically codified in the distressed watershed rules, a multitude of other best management practices (BMPs) and conservation practices such as filter strips, buffers, cover crops, manure transfers, and manure storage areas began increasing in regularity during this time to further reduce runoff rates (Pearce and Yates, 2017; Richards et al., 2008). These practices have been shown to be effective in other watersheds, yielding nutrient concentration reductions ranging from minimal to highly relevant (up to 40–50%) but do appear to relate heavily to time since implementation, type of practice, season, adoption rate, and even field percentage that is tile drained (Inamdar et al., 2001; Makarewicz et al., 2009).

Although manure can be problematic from a runoff perspective, it is also an important source of nutrients, and its use as a regular source of fertilizer has increased over recent years as a result of availability, financing, soil health, nutrient levels, and yield implications (Khaleel et al., 1980, Russelle et al., 2007; Srinivasan et al., 2006; Witzel et al., 1969). It is estimated that in the United States, approximately 5.4 and 1.6 million t of N and P, respectively, are produced from manure-based fertilizers, with the bulk of the use occurring in the Midwest (Puckett, 1995). In the GLSM watershed, approximately 420,000 t of manure (~2750 and 820 t of N and P, respectively) are produced annually across the 241-km^2 watershed (GLWWA 2008). Unfortunately, an application percentage of manure compared with commercial-based nutrients is not available. However, when manure production is compared to standard corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] agronomic recommendations in the tristate fertilizer recommendations guide (Vitosh et al., 1995), estimates indicate approximately 1.5 times more P and 2 times more N are produced annually than needed for a standard rotation, suggesting that a majority of nutrients applied are manure based.

Manure is typically applied in a surface or subsurface slurry (Khaleel et al., 1980); however, due to the high potential for runoff, the manner and timing of its application warrants study (Carpenter, 2005; Lorimor and Melvin, 1996). Manure that is applied in excess, adjacent to sensitive areas, along too steep of landscape gradients, to unstable soil conditions (e.g., porous, impervious), to empty fields, or during high precipitation events can quickly run off via drainage routes and contribute to elevated N and P in streams (Hoorman et al., 2005a,b; Hoorman and Shipitalo, 2006; Puckett, 1995). Application during winter months exacerbates these conditions as snow and ice coupled with the unpredictability of spring melting and precipitation contribute a significant portion of yearly runoff in a few isolated events (Converse et al., 1976; Fleming and Fraser, 2000; Kongoli and Bland, 2002; Molnau and Cherry, 1990; Stuntebeck et al., 2011; Young and Mutchler, 1976). As a result, winter manure bans and a host of BMPs focused on manure management have been implemented in a number of North American watersheds. Exact practice numbers for BMPs in addition to the winter manure ban in GLSM are difficult to obtain on a voluntary level. The USDA Environmental Quality Incentive Program (EQIP) data, however, indicate increased funding of these BMPs in the months leading up to and immediately following the 2011 designation change that effectively doubled the number of dollars spent in the watershed (from less than \$1 million annually to some years in excess of \$2 million; NRCS, 2010–2013). Although EQIP provides a funding source to support BMPs, it does not represent the sole record of their adoption. However, it can still serve to gauge interest in these practices. At a watershed level, funding from 2010 to 2013 supported manure transfers (~230,000 total t primarily during the fall 2011 season), construction of manure storage facilities (~80+ with majority constructed 2013), and implementation of other BMPs (~40+ ha of filter strips, buffers, and grass waterways as well as 5000+ ha of cover crops). There is a definite need for more watershed studies pertaining to the efficiency of manure focused BMPs (see Srinivasan et al., 2006).

The focus of this study was on assessing seasonal and annual nutrient changes of streams in the GLSM watershed (northwest Ohio) following the distressed watershed designation of 2011. Specifically, the objectives of this study were to describe trends in total suspended solids (TSS) and nutrients (particulate phosphorus, PP; soluble reactive phosphorus, SRP; nitrate–N, NO_3^-; and total Kjeldahl N, TKN) in one of the major tributaries to Grand Lake—Chickasaw Creek—over the past decade to assess the efficacy of recently implemented management and conservation practices. Because multiple practices and approaches coincide with the 2011 distressed watershed designation, we do not attempt to parse out the efficacy of one BMP versus another. Rather, we predicted that TSS and nutrients would covary with stream discharge and that when these were held constant, there would be measureable long-term improvements in water quality.

Materials and Methods

Study Area

Grand Lake St Marys watershed is located in Mercer and Auglaize counties in northwestern Ohio (Fig. 1). The 241-km^2 watershed is composed of approximately six first- and second-order tributaries that drain into the largest reservoir in Ohio (mean surface area: 52 km^2; mean volume: 8.25×10^7 m^3; mean residence time: 236 d; Filbrun et al., 2013). The watershed configuration, including the reservoir, is the result of a series of construction efforts to reroute streams, excavate the reservoir, and drain landscapes dating back to 1837 to 1845 to supply water to the Miami–Erie Canal (Clark 1960). The intended historical use combined with the geographical locale of the watershed has situated GLSM as an important study area as it serves as an artificial connection between the Ohio River and Lake Erie drainages. Today, the reservoir functions as a recreational destination and public resource (fishing, sports, drinking water, etc.) for the surrounding communities (Clark, 1960). The use categorization for the watershed is primarily agriculture, which is composed of 80 to 90% crop land (corn, soybean, wheat [*Triticum aestivum* L.], pasture), with a large percentage of these operations maintaining livestock production facilities (dairy, swine, poultry, turkey, and beef; total number ~370 animal units km^{-2}; see Filbrun et al., 2013; GLWWA, 2008; Hoorman et al., 2008). According to countywide USDA statistics, the percentages of agricultural land and total animals have remained largely consistent across

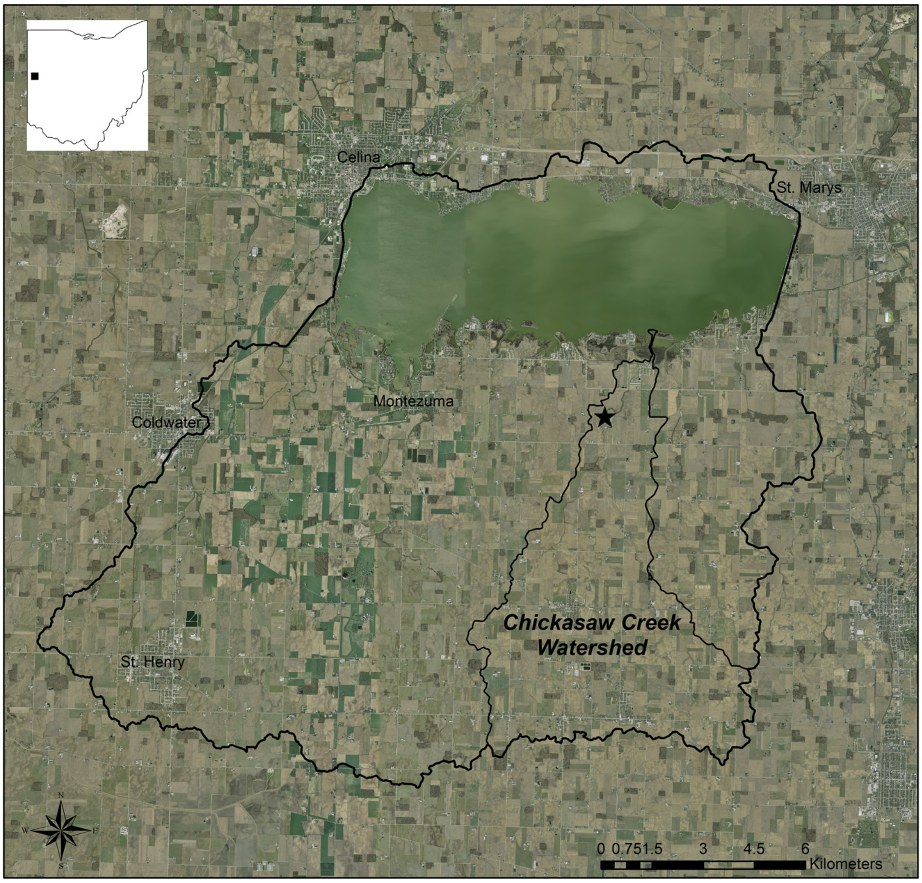

Fig. 1. Subwatershed map of Chickasaw Creek with surrounding Grand Lake St. Marys watershed. Star symbol indicates location of long-term Heidelberg water quality monitoring station. Chickasaw Creek subwatershed drains ~25% of total Grand Lake St. Marys watershed land area.

the past decade, exhibiting a change between the 2007 and 2012 census periods of <5% difference in either category (USDA, 2009, 2014).

Sample Collection and Analysis Protocol

All data were collected from Chickasaw Creek as part of the National Center for Water Quality Research (Heidelberg University) long-term monitoring program (Fig. 1). This station was used as it is the only long-term station in the watershed with data that spans before and after the distressed regulation. This station is representative of the watershed as it drains a significant portion (~25% of total land area) and exhibits similar soils, tile drainage, stream types (e.g., channelized), land uses of approximately 80 to 90% crop, and percentages of animal-based production (with the exception of higher chicken percentages) as the entire GLSM watershed (GLWWA, 2008; Ohio EPA, 2007). Similarly, Chickasaw Creek accounted for comparable BMP implementation rates as >90% of the acreage maintains nutrient management plans and the subwatershed represents 60 and 30% of overall year-round manure transport (average of 7 yr^{-1}) and storage structures (average of 13 yr^{-1}), respectively, from EQIP funding.

In this study, water samples were collected three times daily (every 8 h) by refrigerated automatic samplers (Isco). Samples were retrieved weekly for laboratory analysis where all samples were analyzed during periods of high flow (e.g., storm runoff determined by NCWQR) or a single midday sample during periods of baseflow. All water quality analyses followed standard USEPA methodologies (National Center for Water Quality Research, 2017). Total suspended solid concentrations were measured using the gravimetric method determined by comparing starting to filtered mass of a dry glass fiber (0.7 μm). Phosphorus (total P [TP] and SRP) and TKN concentrations were measured using colorimetric procedures where PP was calculated as the difference between unfiltered TP and filtered (0.45-μm membrane filters) SRP concentrations (sensu Baker et al., 2014). Nitrate–N and nitrite–N concentrations were measured using ion chromatography of filtered samples; hereafter the sum of nitrate and nitrite is referred to as NO_3^-.

Because any water quality measurement represents a single point sample, daily flow-weighted mean concentrations (FWMCs) were calculated to infer concentrations across a given daily period. The FWMCs were calculated by dividing the daily load, determined as the product of the sample sum for a given day, by flow for a given time interval, with daily FWMC interpolated by hand for missing points (<5% of the time; see Richards et al., 2008). Flow data was from the corresponding USGS stream gauging station located at the point of sample collection (USGS 402913084285400, Chickasaw Creek at St. Marys, OH). Before statistical analyses, all flow data were converted to million cubic meters and analytical results were adjusted to daily FWMCs and reported as milligrams per liter.

Statistical Analysis

Daily flow-weighted mean concentrations of TSS, PP, SRP, NO_3^-, and TKN were modeled separately using a general linear model (GLM) to assess differences in concentration before and after the 2011 distressed rules were put in place. The GLM was used in preference to more classic linear models (e.g., regression, ANOVA) to accommodate the variance and distribution inherent in the majority of water quality data. Specifically, a γ distribution (log link function) was used in the GLM to accommodate the positive distribution of the non-negative untransformed water quality data (de Souza Beghelli et al., 2016; Zuur et al., 2009). In addition to modeling FWMC data as a function of time period (pre- and post-distressed regulation), flow and manure application period (application vs. ban) were also included as model parameters.

Data were grouped according to time (pre-regulation, before 19 Jan. 2011; post-regulation, after 19 Jan. 2011) and manure application period (manure ban period, 15 December–1 March; manure application period, 2 March–14 December). Since FWMCs were expected to increase with flow, an interaction term (flow × time) was used to account for potential differences in flow rates between time periods. To avoid redundancy, account for multicollinearity, and reduce error, given the variation in flow over time as well as the grouping time variable coinciding with manure regulatory periods, no two- or three-way interaction terms between manure application period × time or manure application period × flow × time were included in the final model. Multicollinearity among model parameters was assessed using the variance inflation factor statistic (cutoff of 2.5) before running. To easily visualize water quality parameters in light of the nested categories, interval plots of nutrient FWMC point estimates bracketed by 95% confidence intervals were arranged by 33.3% flow percentiles (representing low-, medium-, and high-flow data rather than separating data into three even groups), manure application period (application vs. ban periods), and pre- or post-2011 distressed regulation to visualize differences by variable. Statistical significance was assessed using a *P* value cutoff of <0.05. All analyses were done using the base stats package in the R statistical environment (R Core Team, 2016).

Results

A total of 2880 FWMC values for each water quality parameter were calculated from Chickasaw Creek water samples pulled between 1 Oct. 2008 and 30 Sept. 2016. Flow rates over this time period ranged from 0 to 2.5 million m^3 d^{-1} (mean flow [*Q*]: 0.045, SE 0.003; Fig. 2). Concurrently, FWMC of TSS ranged from 0.5 (below detection limit [BDL]) to 1245.3 mg L^{-1} (mean TSS: 22.5, SE 1.0), PP ranged from 0.001 (BDL) to 1.53 mg L^{-1} (mean PP: 0.104, SE 0.002), SRP ranged from 0.001 (BDL) to 1.97 mg L^{-1} (mean SRP: 0.21, SE 0.003), NO_3^- ranged from 0.001 (BDL) to 43.3 mg L^{-1} (mean NO_3^-: 7.9, SE 0.12), and TKN ranged from 0.01 (BDL) to 71.9 mg L^{-1} (mean TKN: 1.3, SE 0.04). See Table 1 for mean parameter values by time (pre-vs. post-distressed regulation), manure application period (manure ban vs. application period), and flow category.

Overall, GLM results identified flow as the primary driver of variation among parameters (Tables 1, 2). In addition to flow, distinct differences between pre- and post-distressed watershed as well as within-year variation coinciding with the manure ban

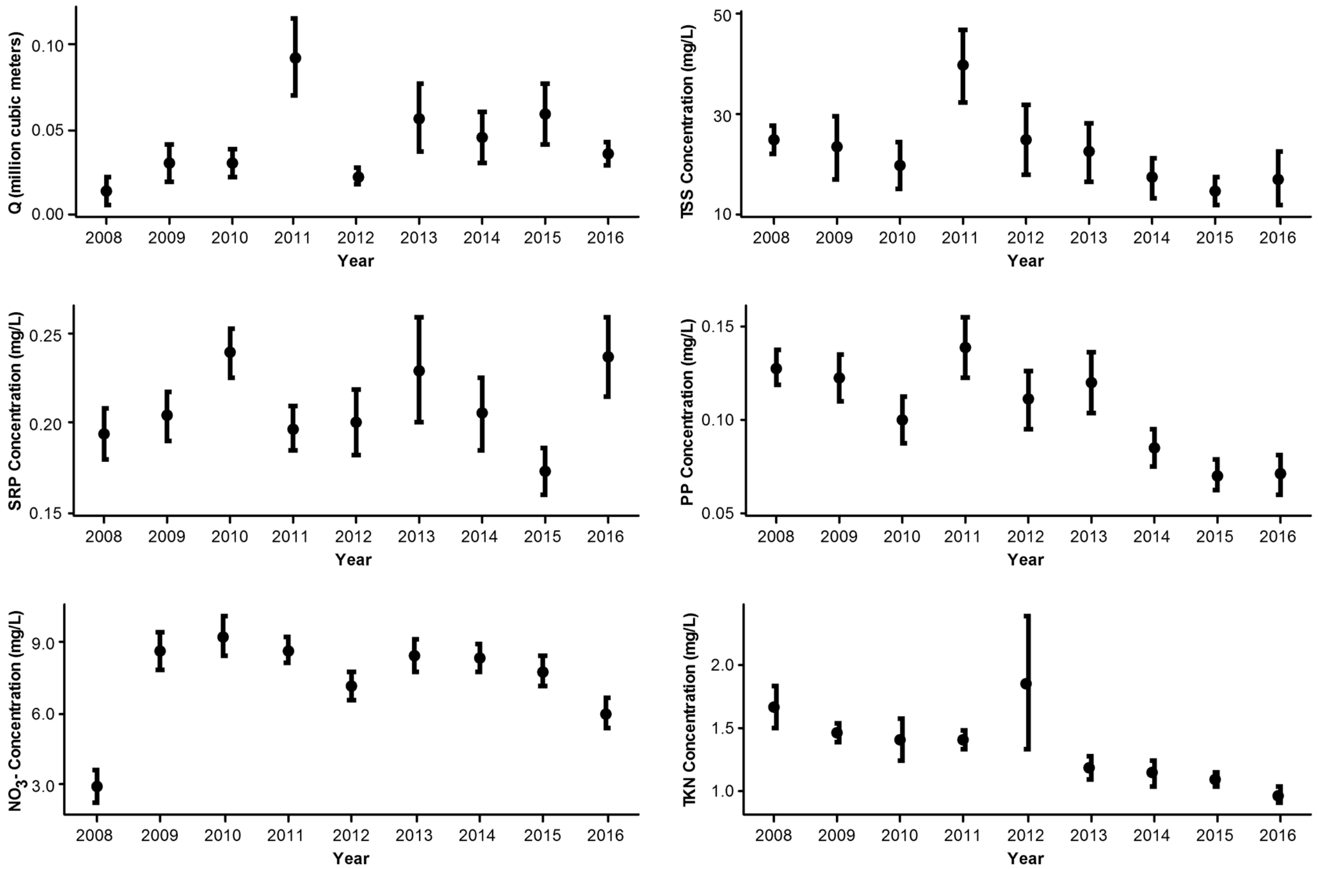

Fig. 2. Annual discharge, sediment, and nutrient loads with time. Discharge (*Q*) is average annual daily discharge (million cubic meters); sediment and nutrient concentrations are in milligrams per liter. 2008 and 2016 are partial years (beginning and ending with water years October and September, respectively); thus, mean and variation are not reflective of the entire annual period. PP, particulate P; SRP, soluble reactive P; total Kjeldahl nitrogen; TSS, total suspended solids.

Table 1. Summary data and statistics describing water quality measurements over time in Chickasaw Creek (Grand Lake St. Marys watershed, Ohio).

Flow category	Complete monitoring period							Manure ban period (15 Dec. 15–1 Mar.)							Manure application period (2 Mar.–14 Dec.)						
	Pre-regulation			Post-regulation				Pre-regulation			Post-regulation				Pre-regulation			Post-regulation			
	N	Mean	SE	*N*	Mean	SE	% change	*N*	Mean	SE	*N*	Mean	SE	% change	*N*	Mean	SE	*N*	Mean	SE	% change
		– mg L^{-1} –			– mg L^{-1} –		%		– mg L^{-1} –			– mg L^{-1} –		%		– mg L^{-1} –			– mg L^{-1} –		%
											Total suspended solids										
Low	409	11.2	0.5	551	11.9	0.5	+6	75	10.4	1.6	27	10.6	2.6	+2	334	11.4	0.6	524	11.9	0.5	+4
Medium	235	10.4	0.5	734	9.8	0.5	–6	68	9.1	0.8	174	5.8	0.4	–36	167	10.9	0.58	560	11.03	0.6	+1
High	196	57.9	6.7	755	43.4	3.1	–25	44	53.5	13.1	222	37.8	4.9	–29	152	59.2	8.1	533	45.7	3.4	–23
											Particulate P										
Low	409	0.1	0	551	0.09	0	–10	75	0.11	0.01	27	0.05	0.01	–55	334	0.1	0.002	524	0.09	0.004	–10
Medium	235	0.08	0.01	734	0.06	0	–25	68	0.07	0.01	174	0.03	0.002	–57	167	0.08	0.01	560	0.07	0.003	–13
High	196	0.19	0.02	755	0.14	0.01	–26	44	0.24	0.04	222	0.13	0.01	–46	152	0.17	0.02	533	0.15	0.01	–12
											Soluble reactive P										
Low	409	0.25	0.01	551	0.21	0.01	–16	75	0.23	0.01	27	0.12	0.02	–48	334	0.25	0.01	524	0.21	0.007	–16
Medium	235	0.17	0.01	734	0.2	0.01	+18	68	0.18	0.01	174	0.13	0.01	–28	167	0.16	0.01	560	0.23	0.01	+44
High	196	0.22	0.01	755	0.21	0.01	–5	44	0.22	0.01	222	0.18	0.01	–18	152	0.22	0.01	533	0.22	0.01	0
											Nitrate–N										
Low	409	2.3	0.2	551	2.1	0.1	–9	75	7.3	0.25	27	7.2	0.64	–1	334	1.2	0.13	524	1.8	0.1	+50
Medium	235	11.8	0.4	734	7.7	0.2	–35	68	12.4	0.48	174	10.4	0.2	–16	167	11.6	0.46	560	6.8	0.2	–41
High	196	17.1	0.5	755	11.9	0.2	–30	44	14.4	0.82	222	11.6	0.26	–19	152	17.85	0.52	533	12.12	0.24	–32
											Total Kjeldahl N										
Low	409	1.3	0.04	551	1.3	0.1	0	75	1.4	0.06	27	0.85	0.08	–39	334	1.26	0.04	524	1.3	0.1	+3
Medium	235	1.3	0.1	734	1.1	0.1	–15	68	1.3	0.09	174	0.76	0.04	–42	167	1.4	0.12	560	1.2	0.09	–14
High	196	1.9	0.1	755	1.4	0.1	–26	44	2.5	0.21	222	1.6	0.32	–36	152	1.8	0.14	533	1.4	0.04	–22

period were found to be highly significant in driving parameter estimates. However, these variables were not always independent as flow was found to be significantly higher in pre-2011 (840 FWMC days, mean Q: 0.053) compared with post-2011 (2040 FWMC days; mean Q: 0.028) regulation time periods (Student's *t* test: *t* value 5.4, $P < 0.001$). After incorporating and accounting for these covariates in the GLM, statistically significant reductions (independent of flow interactions) in TSS, PP, and NO_3^- were noted following the 2011 period as well as within year during winter months coinciding with the implementation of the manure application ban (Tables 1, 2, Fig. 2–4). Additionally, while no significant interaction terms between flow and time period were detected in SRP and TKN models, both of these indicated significant reductions following the implementation of the manure ban in the main effects (Tables 1, 2, Fig. 2–4).

Across all years and flow categories, mean concentration reductions were most apparent when comparing pre- and post-distressed watershed periods during medium and high flows

Table 2. General linear model configurations and results.

Water quality parameter (mg L^{-1})	Effect†	Estimate	SE	*t* value	*P*
Total suspended solids	Q	5.78	0.25	23.3	<0.001
	Time	0.01	0.08	0.03	0.98
	Manure application period	–0.31	0.08	–3.8	<0.001
	$Q \times$ time	3.84	0.74	5.2	<0.001
Particulate P	Q	3.13	0.14	22.6	<0.001
	Time	0.23	0.04	5.3	<0.001
	Manure application period	–0.30	0.05	–6.5	<0.001
	$Q \times$ time	1.03	0.42	2.5	0.01
Soluble reactive P	Q	0.62	0.11	5.4	<0.001
	Time	0.09	0.04	2.6	<0.001
	Manure application period	–0.26	0.04	–6.9	<0.001
	$Q \times$ time	0.12	0.34	–0.3	0.73
Nitrate–N	Q	1.17	0.12	10.1	<0.001
	Time	–0.07	0.04	–1.9	0.06
	Manure application period	0.42	0.04	11.1	<0.001
	$Q \times$ time	4.86	0.35	13.8	<0.001
Total Kjeldahl N	Q	1.36	0.2	6.7	<0.001
	Time	0.14	0.06	2.3	0.02
	Manure application period	–0.10	0.07	–1.5	0.14
	$Q \times$ time	0.71	0.61	1.2	0.25

† Q, flow; time, pre- vs. post-distressed watershed; manure application period (ban vs. application period).

including overall reductions across all flow categories amounting to −8% for TSS (~4.8 mg L^{-1}), −20% for PP (~0.03 mg L^{-1}), −1% for SRP (~0.01 mg L^{-1}), −25% for NO$_3^-$ (~3.2 mg L^{-1}), and −14% for TKN (~0.23 mg L^{-1}). One exception was an 18% increase in SRP concentrations at medium flows (~0.03 mg L^{-1}), likely occurring as a result of changes in application timing following the distressed rules package. Not surprisingly, since the primary component of the distressed rules package (e.g., manure ban) coincides with the nongrowing season, these reductions were much more apparent during the winter ban months than outside of this season. Across flow percentiles, mean concentration reductions during the months directly influenced by the manure ban were noted as −21% for TSS (~6.3 mg L^{-1}), −53% for PP (~0.07 mg L^{-1}), −31% for SRP (~0.07 mg L^{-1}), −12% for NO$_3^-$ (~1.6 mg L^{-1}), and −39% for TKN (~0.66 mg L^{-1}). While values outside of the immediate ban were much more variable and not as substantive in many cases, there were still overall reductions up to ~40% in some nutrients noted when comparing pre- to post-distressed watershed periods. We interpret this as evidence that other practices such as nutrient management plans, manure transfers out of the watershed, manure storages, filter strips, buffers, cover crops, and so on, which were also beginning to be implemented around 2011, were having some effect (Table 1). It should also be noted that on average, the highest reductions in the manure ban period tended to occur at low to intermediate flow percentiles, while the highest reductions in nutrients during periods of the year when manure application was possible occurred at higher flows, having more implications for loading (Table 2, Fig. 3–4).

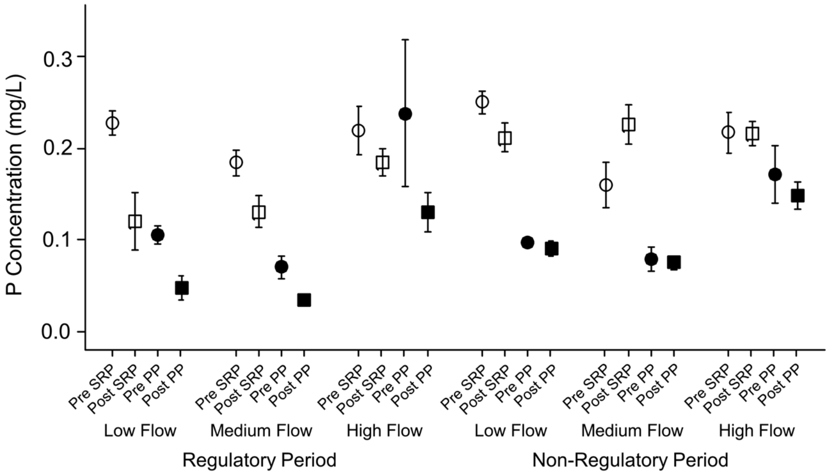

Fig. 3. Soluble reactive P (SRP; open shapes) and particulate P (PP; closed shapes) flow-weighted mean concentration (mg L^{-1}) 95% confidence interval (SE) plot arranged by flow (third percentiles), manure application period (application denoted by circles vs. ban denoted by squares), and time (pre- vs. post-distressed watershed).

Discussion

In this study, we identified decreasing daily FWMC of TSS, PP, SRP, NO$_3^-$, and TKN consistent with the 2011 implementation of the distressed watershed with the largest reductions coinciding with the winter manure ban. Our results are consistent with or exceed those documented in past manure ban and BMP research where reductions ranged from 10 to 20% for N to 5 to 15% for P (Converse et al., 1976; Hensler et al., 1970; Minshall et al., 1970; Pearce and Yates, 2017; Phillips et al., 1975). Although some critics of manure bans may point to the unpredictability of freezing or precipitation as reasons for adopting a case-by-case management approach, the relationships between manure application and runoff are often complicated. These complications could potentially introduce errors as past survey methodologies in Ohio have shown the potential for general confusion among many producers as to the factors that link application and runoff (Hoorman et al., 2005a,b). We recommend that producers in the GLSM region continue to follow stewardship guidelines associated with appropriate manure management in place in this distressed watershed. If winter applications would resume, we recommend they be monitored on an individual basis, using periods of unfrozen ground with subsequent incorporation rather than surface spreading.

Importantly, changes also occurred outside the manure regulatory period. We attribute these improvements to nutrient management plans and an assortment of BMPs. Unfortunately, one particular instance was found at medium flows wherein SRP exhibited a clear increase in concentration outside of the manure ban (raw data indicate this occurred in April and May). Although there was no change in SRP at higher flows outside of the regulatory period, these patterns indicate that additional discussion is warranted. This trend at medium flows likely indicates changes in application timing whereby manure not spread during the winter is spread at increased rates following the opening of the application period. This does not necessarily indicate a failure to follow a management plan, however, as it is possible that the manure spread during this new truncated pre-plant time is necessary to maintain an appropriate agronomic range (informed by soil testing). Furthermore, while practices such as the manure

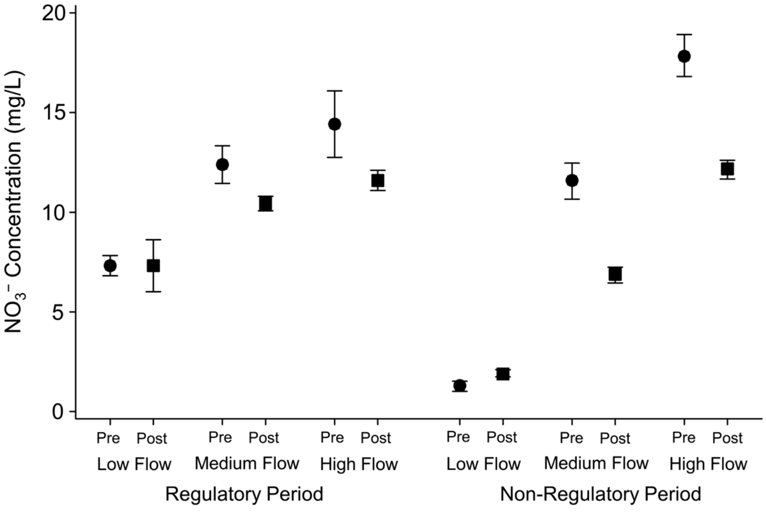

Fig. 4. Nitrate flow-weighted mean concentration (mg L^{-1}) 95% confidence interval (SE) plot arranged by flow (third percentiles), manure application period (application vs. ban period), and time (pre- vs. post-distressed watershed).

ban, storage lot construction, or transfers are linked, they are not necessarily dependent, meaning that it may not be possible to mitigate heavier single applications by exporting everything or maintaining longer storage. Although one might expect to see a similar increase in N runoff during the post-regulation period, this could be due to the fact that if manure being applied has been stored for the winter it has likely lost a higher proportion of N relative to more stable forms of P, which are known to persist longer under storage (NRCS, 1999). More research in spring application timing as well as avenues to eliminate any potential accumulation or transfer needs should be conducted.

In a recent review, Sharpley et al. (2013) pointed out that despite growing numbers of watershed level conservation practices that have been implemented over the past several decades, positive changes to water quality have been slow to manifest as a result of the many more decades of damaging land management practices. This study provides encouraging results over a fairly short time period relative to reductions in nutrients and sediment resulting in improved water quality in the region. Unfortunately, and in line with commentary related to legacy effects (Sharpley et al., 2013), complete changes in the GLSM watershed will likely be slow to manifest. Soil test P (STP) analyses from 2000 to 2012 in the GLSM watershed found median Mehlich 3 STP levels in excess of 75 mg kg^{-1}. These elevated soils, attributed to the high concentration of animal production, are significantly higher than almost every other subbasin in Ohio, where 39 out of 41 (hydrologic level 8) have been found to be within the standard 21 to 71 STP agronomic range (Ohio Lake Erie Phosphorus Task Force, 2013). The high degree of animal-based agriculture was captured in the USDA Census Reports where Mercer County is noted to have approximately 300,000 total animal units of cows, pigs, and poultry; a number that has been largely consistent since the implementation of the distressed watershed rules (Ohio EPA, 2007; USDA, 2009, 2014). It is plausible that the elevated soil levels noted in GLSM are providing a P reservoir, as previous research has shown the strong relationship between STP levels and P runoff (McDowell and Sharpley, 2001; Sibbesen and Sharpley, 1997). Unfortunately, STP values are not known to change rapidly, even independent of application patterns (Ohio Lake Erie Phosphorus Task Force, 2013). These high reservoirs must be reduced while monitoring agronomic production to provide a better estimation of any potential effect that continued conservation practices in the region may have on SRP.

A decade ago, the Ohio EPA ranked the GLSM watershed as one of the top 10 most impaired watersheds in the state of Ohio (Ohio EPA, 2007). As part of this 2007 Ohio EPA total maximum daily load (TMDL) report, it was found that no stream in the watershed met the criteria for "healthy" warm water habitat. The degradations facing GLSM are watershed-wide and include both physical and chemical habitat impairments that should not be considered independent as a complex array of habitat alterations undergirds these issues. The nutrient TMDL criteria established by Ohio EPA (2007) used sites across Ohio in a comprehensive database to provide target values for NO_3^- and TP by drainage area (headwaters, wadable, and small rivers). The wadable category includes any stream with a drainage area between ~50 and 500 km^2; criteria for NO_3^- and TP were 1.0 and 0.10 mg L^{-1}, respectively. Before the distressed watershed rules, no stream in the watershed met these TMDL goals, and the majority of the streams (including Chickasaw Creek) necessitated load reductions of >90% across flows.

The findings of this study indicate that while impressive reductions have occurred, nutrient loading continues to be a challenge in the watershed as mean annual nutrient concentrations remain well above suggested target TMDL baselines (NO_3^- and TP averaged 7.7 and 0.26 mg L^{-1} at medium flows, respectively). When compared to other surface waters in agricultural watersheds across the United States, these levels fall around the 75th percentile (Dubrovsky and Hamilton, 2010). Future conservation efforts in the watershed should focus on approaches that reduce both concentration and runoff volume. Some of these focuses could potentially include innovative cropping rotations, drainage water control, tile drain bioreactors and sorption beds, saturated buffers, blind inlets, additional filter strips or grass waterways, two-stage ditches, constructed wetlands, and continued adoption of the 4R Nutrient Stewardship program (right fertilizer source, at the right rate, at the right time, in the right place). A hybridized approach of multiple conservation practices should be used to further reduce nutrient loading in the watershed as a single approach is unlikely to be feasible or effective (Pearce and Yates, 2017). Continued monitoring to assess efficacies of various watershed remediation approaches coupled with extension activities to raise awareness is needed.

Conclusion

Notable changes in water quality of the GLSM watershed occurred following implementation of the 2011 distressed rules package. These changes were most pronounced during the winter manure ban but were also apparent year round and are attributed to implementation of the manure ban, nutrient plans, grass waterways, manure storage structures, manure transport, cover crops, etc. Although concentration reductions were evident at all flows, the most important reductions occurred during high winter flow periods across all parameters: TSS: −15.7 mg L^{-1} (~29%), PP: −0.11 mg L^{-1} (~46%), SRP: −0.04 mg L^{-1} (~18%), NO_3^-: −2.8 mg L^{-1} (~19%), and TKN: −0.9 mg L^{-1} (~36%). While these new values still do not meet suggested criteria for nutrient levels, they do represent an important step in that direction. We suggest that additional watershed conservation practices and monitoring be undertaken to continue to improve GLSM water quality.

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References

Baker, D.B., R. Confesor, D.E. Ewing, L.T. Johnson, J.W. Kramer, and B.J. Merryfield. 2014. Phosphorus loading to Lake Erie from the Maumee, Sandusky, and Cuyahoga Rivers: The importance of bioavailability. J. Great Lakes Res. 40:502–517. doi:10.1016/j.jglr.2014.05.001

Carpenter, S.R. 2005. Eutrophication of aquatic ecosystems: Bistability and soil phosphorus. Proc. Natl. Acad. Sci. USA 102:10002–10005. doi:10.1073/pnas.0503959102

Clark, C.F. 1960. Lake St. Marys and its management. Ohio Department of Natural Resources, Division of Wildlife. Columbus.

Converse, J.C., G.D. Bubenzer, and W.H. Paulson. 1976. Nutrient losses in surface runoff from winter spread manure. Trans. ASAE 19:0517–0519.

de Souza Beghelli, F.G., D. Frascareli, M.L.M. Pompêo, and V. Moschini-Carlos. 2016. Trophic state evolution over 15 years in a tropical reservoir with low nitrogen concentrations and cyanobacteria predominance. Water Air Soil Pollut. 227:95. doi:10.1007/s11270-016-2795-1

Dubrovsky, N.M., and P.A. Hamilton. 2010. Nutrients in the nation's streams and groundwater: National findings and implications. USGS Fact Sheet 2010-3078. USGS, Reston, VA.

Filbrun, J.E., J.D. Conroy, and D.A. Culver. 2013. Understanding seasonal phosphorus dynamics to guide effective management of shallow, hypereutrophic Grand Lake St. Marys, Ohio. Lake Reservoir Manage. 29:165–178.

Fleming, R., and H. Fraser. 2000. Impacts of winter spreading of manure on water quality: Literature review. Ridgetown College, University of Guelph, Ridgetown, ON, Canada. https://www.ridgetownc.com/research/documents/fleming_manure.pdf (accessed June 2017).

Grand Lake/Wabash Watershed Alliance (GLWWA). 2008. Grand Lake St. Marys/Wabash River watershed action plan: A partnership between Soil and Water Conservation Districts. Darke, Auglaize, and Mercer Counties and the city of Celina. https://water.ohiodnr.gov/portals/soilwater/downloads/wap/Wabash.pdf.

Hensler, R.F., R.J. Olsen, S.A. Witzel, O.J. Attoe, W.H. Paulson, and R.F. Johannes. 1970. Effect of method of manure handling on crop yields, nutrient recovery and runoff losses. Trans. ASAE 13:0726–0731.

Hoorman, J., T. Hone, T. Sudman, Jr., T. Dirksen, J. Iles, and K.R. Islam. 2008. Agricultural impacts on lake and stream water quality in Grand Lake St. Marys, western Ohio. Water Air Soil Pollut. 193:309–322. doi:10.1007/s11270-008-9692-1

Hoorman, J.J., S.C. Prochaska, J.N. Rausch, and M. Fritz. 2005a. Ohio dairy farm manure application survey. Ohio J. Sci. 104:A-34.

Hoorman, J.J., S.C. Prochaska, J.N. Rausch, and M. Fritz. 2005b. Ohio swine farm manure application survey. Ohio J. Sci. 104:A-34.

Hoorman, J.J., and M.J. Shipitalo. 2006. Subsurface drainage and liquid manure. J. Soil Water Conserv. 61:94–97.

Inamdar, S.P., S. Mostaghimi, P.W. McClellan, and K.M. Brannan. 2001. BMP impacts on sediment and nutrient yields from an agricultural watershed in the Coastal Plain Region. Trans. ASAE 44:1191–1200. doi:10.13031/2013.6449

Khaleel, R., K.R. Reddy, and M.R. Overcash. 1980. Transport of potential pollutants in runoff water from land areas receiving animal wastes: A review. Water Res. 14:421–436. doi:10.1016/0043-1354(80)90206-7

Kongoli, C.E., and W.L. Bland. 2002. Influence of manure application on surface energy and snow cover. J. Environ. Qual. 31:1166–1173. doi:10.2134/jeq2002.1166

Lorimor, J.C., and J.C. Melvin. 1996. Nitrogen losses in surface runoff from winter-applied manure. Final Report. University of Iowa.

Makarewicz, J.C., T.W. Lewis, I. Bosch, M.R. Noll, N. Herendeen, R.D. Simon, J. Zollweg, and A. Vodacek. 2009. The impact of agricultural best management practices on downstream systems: Soil loss and nutrient chemistry and flux to Conesus Lake, New York, USA. J. Great Lakes Res. 35:23–36. doi:10.1016/j.jglr.2008.10.006

McDowell, R.W., and A.N. Sharpley. 2001. A comparison of fluvial sediment phosphorus (P) chemistry in relation to location and potential to influence stream P concentrations. Aquat. Geochem. 7:255–265. doi:10.1023/A:1015274426411

Mescher, T., and F. Springer. 2013. Grand Lake St. Marys watershed update. Presented at: Lake Improvement Association, Montezuma, OH. 21 Oct. 2013. https://www.slideshare.net/lakeimprovement/grand-lake-st-marys-watershed-update (accessed Sept. 2017).

Minshall, N.E., S.A. Witzel, and M.S. Nichols. 1970. Stream enrichment from farm operations. J. Sanit. Eng. Div. Am. Soc. Civ. Eng. 96:513–524.

Molnau, M., and J.G. Cherry. 1990. A comparison of runoff occurring on frozen and unfrozen soils. In: K.R. Cooley, editor, Proceedings of International Symposium, Spokane, WA. CRREL Special Rep. 90-1. Cold Regions Research and Engineering Laboratory, US Army Corps of Engineers, Hanover, NH. p. 279–281.

National Center for Water Quality Research. 2017. Tributary data download. National Center for Water Quality Research, Heidelberg University. https://ncwqr.org/monitoring/data/.

NRCS. 1999. Agricultural waste characteristics. In: J.N. Krider, and J.D. Rickman, editors, Part 651, Agricultural waste management field handbook. USDA-NRCS, Washington, DC.

NRCS. 2010–2013. Grand Lake St. Mary's watershed special project. USDA-NRCS. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/oh/programs/?cid=nrcs144p2_029521.

Ohio EPA. 2007. Total maximum daily loads for the Beaver Creek and Grand Lake St. Marys watershed. Ohio Environmental Protection Agency, Columbus.

Ohio Lake Erie Phosphorus Task Force. 2013. Ohio Lake Erie Phosphorus Task Force II final report. Ohio Environmental Protection Agency, Columbus.

Pearce, N.J.T., and A.G. Yates. 2017. Intra-annual variation of the association between agricultural best management practices and stream nutrient concentrations. Sci. Total Environ. 586:1124–1134. doi:10.1016/j.scitotenv.2017.02.102

Phillips, P.A., A.J. MacLean, F.R. Hore, F.J. Sowden, A.D. Tenant, and N.K. Patni. 1975. Soil water and crop effects of selected rates and times of dairy cattle liquid manure applications under continuous corn. Engineering Research Service Contribution 540. Agriculture Canada, Ottawa, ON.

Puckett, L.J. 1995. Identifying the major sources of nutrient water pollution. Environ. Sci. Technol. 29:408A–414A. doi:10.1021/es00009a743

R Core Team. 2016. R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria. https://www.R-project.org.

Richards, R.P., D.B. Baker, J.P. Crumrine, J.W. Kramer, D.E. Ewing, and B.J. Merryfield. 2008. Thirty-year trends in suspended sediment in seven Lake Erie tributaries. J. Environ. Qual. 37:1894–1908. doi:10.2134/jeq2007.0590

Russelle, M.P., M.H. Entz, and A.J. Franzluebbers. 2007. Reconsidering integrated crop–livestock systems in North America. Agron. J. 99:325–334. doi:10.2134/agronj2006.0139

Sharpley, A., H.P. Jarvie, A. Buda, L. May, B. Spears, and P. Kleinman. 2013. Phosphorus legacy: Overcoming the effects of past management practices to mitigate future water quality impairment. J. Environ. Qual. 42:1308–1326. doi:10.2134/jeq2013.03.0098

Sibbesen, E., and A.N. Sharpley. 1997. Setting and justifying upper critical limits for phosphorus in soils. In: H. Tunney, et al., editors, Phosphorus loss from soil to water. Center for Agriculture and Biosciences Int., New York. p. 151–176.

Srinivasan, M.S., R.B. Bryant, M.P. Callahan, and J.L. Weld. 2006. Manure management and nutrient loss under winter conditions: A literature review. J. Soil Water Conserv. 61:200–209.

Stuntebeck, T.D., M.J. Komiskey, M.C. Peppler, D.W. Owens, and D.R. Frame. 2011. Precipitation–runoff relations and water-quality characteristics at edge-of-field stations, Discovery Farms and Pioneer Farm, Wisconsin, 2003-8. USGS Scientific Investigations Rep. 2011-5008. USGS, Reston, VA.

USDA. 2009. 2007 census of agriculture. USDA National Agricultural Statistics Service, Washington, DC. https://www.agcensus.usda.gov/Publications/2007/.

USDA, 2014. 2012 census of agriculture. USDA National Agricultural Statistics Service, Washington, DC. https://agcensus.usda.gov/Publications/2012/.

USEPA. 2009. National lakes assessment: A collaborative survey of the nation's lakes. Office of Water and Office of Research and Development, USEPA. Washington, DC.

Vitosh, M.L., J.W. Johnson, and D.B. Mengel. 1995. Tri-state fertilizer recommendations for corn, soybeans, wheat, and alfalfa. Michigan State University Ext. Bull. E-2567. https://soil.msu.edu/wp-content/uploads/2014/06/Tri-State-Fertilizer-Recs-E-2567.pdf (accessed June 2017).

Witzel, S.A., N. Minshall, M.S. Nichols, and J. Wilke. 1969. Surface runoff and nutrient losses of Fennimore watersheds. Trans. ASAE 12:338–341. doi:10.13031/2013.38837

Young, R.A., and C.K. Mutchler. 1976. Pollution potential of manure spread on frozen ground. J. Environ. Qual. 5:174–179. doi:10.2134/jeq1976.00472425000500020013x

Zuur, A.F., E.N. Ieno, N.J. Walker, A.A. Saveiliev, and G.M. Smith. 2009. Mixed effects models and extensions in ecology with R. Springer, New York. doi:10.1007/978-0-387-87458-6