Field-Scale Monitoring of Agricultural Ditches as Conduits of Nitrogen, Phosphorus, and Suspended Sediment in Response to Storm Events and Low-Input Drainage Management: A Case-study of the Tchula Lake Farm

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Runoff from row-crop agriculture is a major source of non-point source aquatic pollution. High concentrations of inorganic N and sediment-bound P that are conveyed in agricultural drainage ditches can lead to eutrophication of receiving waters at both local and regional scales. Concerns regarding accelerated eutrophication have led to a concerted effort toward understanding the movement of nutrients across the landscape and the management of agricultural drainages for water quality remediation. This study monitors field-scale movements of nitrate, ammonia, dissolved P, particulate P and total suspended solids through agricultural ditches over several months preceding and following the implementation of controlled drainage practices including slotted pipes and low-grade weirs. Water samples were collected during non-storm flow conditions and storm events via grab sampling and automated techniques. Nitrate concentrations showed a high degree of variability both spatially and temporally, varying from approximately 0 to 15 ppm. Storm events generally had nitrate concentrations 50% to 100% greater than non-storm flow concentrations. In contrast to oxidized nitrogen, ammonia concentrations generally ranged from 0.1 to 0.3 ppm regardless of time or location. Dissolved inorganic P concentrations ranged from approximately 0 to .5 ppm with mean values an order of magnitude lower than the upper maximums. Total inorganic P and turbidity approached an order of magnitude higher in storm water samples than non-storm flow samples, with mean total inorganic P of approximately 0.5 ppm in non-storm flow samples compared to mean values greater than 1 ppm in storm water samples. Total suspended sediment concentrations were also significantly higher in storm water samples than non-storm flow samples, indicating the likelihood that erosion or sediment resuspension is a major factor in P transport in agricultural drainage ditches.

Introduction

Nonpoint Source Pollution and Agricultural Drainage

The USEPA lists agriculture as the primary source of stream impairment in the United States (USEPA, 2004). Agriculture is also considered by the USEPA to be the third greatest source of impairment to lakes (USEPA, 2004) and wetland systems (USEPA, n.d.). There is some degree of variation in the types of impairment caused by agriculture but impacts related to water quality are ubiquitous (Blann et al., 2009). Sedimentation is the most common cause of decreased water quality in streams and wetlands; whereas nutrient enrichment is the most common cause in lakes (USEPA, 2002).

Sediment and nutrient transport from agricultural landscapes to receiving waters is generally increased by improvements to drainage that decrease surface water storage capacity and increase peak velocities. These alterations not only decrease the potential for settling of sediment and biogeochemical reduction, but they also increase the potential for further erosion and sediment resuspension. This problem has been highlighted by the impact of modern agricultural practices in the Mississippi River watershed on the size of the Gulf of Mexico Hypoxic Zone, known colloquially as the "Dead Zone."

Coastal hypoxia is a common phenomenon worldwide. Anthropogenic hypoxic zones, however, have been implicated in the collapse of productive fisheries in systems as varying from the Baltic Sea to the Black Sea. Though there is currently little evidence that a similar collapse will occur in the northwestern Gulf of Mexico, concern about changes in commercial fish harvest have prompted a concerted effort to decrease the delivery of agricultural nonpoint source pollution, primarily excess N. This effort is a multi-tiered approach that relies upon coordinating a vast monitoring network, using data in the most efficacious models, and developing and validating management practices that decrease sedimentation and nutrient delivery. Many of the practices being considered for row-crop agriculture utilize decreasing nutrient inputs and decreasing nutrient transport at their initial aquatic interface: the drainage ditch.

Drainage ditches have received little study with respect to their relative importance as conduits of sediment and nutrients. In the portion of the Lower Mississippi Alluvial Valley known as the Mississippi Delta, these ditches, whether completely artificial or highly modified streams, comprise a greater proportion of wadeable stream reach than unmodified systems. Historically, in order to ensure that water bodies are meeting designated uses, surface water quality monitoring has focused on large watersheds as a gauge of landscape-level trends, or examined smaller drainage basins that are either a known source of pollution or are considered especially ecologically valuable. The diffuse nature of nonpoint source pollutants, and often variable hydrology in agricultural ditches makes them a logistically challenging subject of study. Their position in the landscape between terrestrial inputs and "natural" receiving waters, as well as their role in sediment delivery via in-stream erosion and resuspension justifies a greater effort at surmounting these challenges. Additionally, given the likelihood of a lag-effect between management implementation and measured improvements to the quality of receiving waters, intensive monitoring of these systems is necessary to establish appropriate baselines with which to judge management practices developed to decrease agricultural nonpoint source pollution.

The objective of this study is to characterize nonpoint source pollution at the field scale by using different sampling methods in ditches draining row-crop agriculture and describe the implementation of water control structures for water quality improvement. Samples were collected from row-crop drainage ditches at a site in the Mississippi Delta and analyzed for total suspended solids (TSS), turbidity, total inorganic P (TIP), dissolved inorganic P (DIP), nitrate-N (NO_{3-}-N) and ammonia-N (NH_{3+}-N). The data presented herein are considered preliminary pending further quality assurance validation.

Watershed and Site Info

The study site is located in the Upper Yazoo Watershed (HUC: 08030206) immediately southeast of Eagle Lake and empties into Tchula Lake, a narrow, sinuous oxbow lake of approximately 460 acres that, in turn, empties into the Yazoo River. In 2006 the state of Mississippi reported to the EPA impairments caused by nutrients, sedimentation, and organic enrichment/low dissolved oxygen (USEPA, 2006). Initial data collection began 1/26/11. Seven ditches on the site are being periodically monitored for nonpoint source pollutants. Only four of these ditches (numbered 1-4 in Figure 1) have data from the spring of 2011 and are currently being monitored using the complete sampling protocol described below. Only data from these four ditches is presented in this manuscript. The ditches varied in width from less than three meters at the inflows to nearly 15 meters at outflows (Figure 2). Other relevant information about the ditches is presented in Table 1. During the monitoring period, the site was planted in corn, cotton, and soybeans and much of the site was periodically irrigated with alluvial groundwater via center-pivot irrigation. Less than 40% of the drainage area of Ditch 1 was planted in row-crops, while the drainage areas of the other three ditches were over 95% row crop agriculture. The non-agricultural portion of Ditch 1 is comprised primarily of bottomland hardwoods that were converted from farmland between 1996 and 2004. A small (<1 hectare) body of open water was established during the same period. The remainder of the drainage area of Ditch 1 consists of an estimated 4.5 hectares of emergent palustrine wetland and 7 hectares of forested palustrine wetland. Although it appears in aerial imagery from 1996 that these wetlands were already present, only a very small portion of the present area was listed in the USFWS Wetlands Survey of the area performed in 1974. During the summer of 2011 all ditches were dredged and re-graded. Low-grade weirs and slotted pipes were installed on Ditches 2-3 (Table 1; Figure 3). Water samples were not collected during construction, but as the summer of 2011 was unusually dry, few, if any storm events that would have resulted in significant surface flows were missed. Ditch 1 was straightened and a large volume of unconsolidated sediment was removed, but no weirs or slotted pipes were installed. In August the banks and upper slopes of Ditches 2-3 were seeded with Bermuda grass and the beds/slopes were hydro-seeded with a mixture composed primarily of millet, smartweed, and rice

Methods

Sample Collection

Ditches were monitored using three sampling methods: grab samples, electronic sample collectors (Automated Isco 6712), and fixed-height, passive storm water collectors (referred to hereafter as storm). Grab samples were collected at fixed sampling points prior to implementation of drainage management, and immediately upstream of weirs following implementation. Grab samples were scheduled to be collected at pre-determined sampling points along the length of the ditch (approximate locations in Figure 1) at least every three weeks from March-October and at least every six weeks from November-February. If no flowing water was present in the ditches during the scheduled sampling time, however, no sample was collected. Following weir construction grab samples were collected either at the weir outflow or directly upstream of the weir, depending upon sampling conditions.

Isco samplers were located at the field outlets. The samplers were programmed to begin collecting storm water samples when the water level was 10cm above the intake hose. The hose itself was located in the thalweg approximately 5-10cm above the bed of the ditch. Following initiation of sampling, individual samples were collected in 1-liter polyethelene bottles at 10-minute intervals for one hour and one-hour intervals thereafter, for a potential total of 24 samples spanning a 19-hour period. Constructed storm samplers were deployed along the length of the ditch at the same locations as grab sampling points. Samplers were set at heights from 15-55 cm depending upon the expected water depth and microphotography. At sampling points where the water depth was regularly expected to exceed one meter during storm flows, an additional sampler was set 30-55 cm above the bottom sampler (Figure 3). The units were assembled in-house using PVC pipe and a self-sealing ball valve. They are constructed to passively collect a 650mL water sample at a fixed height on the rising limb of the storm hydrograph. Following construction of weirs, sampling points were shifted from between 0-3 m to sample weir outflow. Isco and storm samples were collected within 48 hours of the estimated collection time. All samples were placed on ice and transported to the water quality laboratory of the MSU Dept of Wildlife, Fisheries, and Aquaculture for analyses. Table 2 presents a summary of the number of samples analyzed for dissolved nonpoint source pollution by ditch and sampling method. A subset of these samples was analyzed for particulate pollution. With the exception of Ditch 1, each ditch had a minimum of 19 samples of each sampling method analyzed for Turbidity and 24 analyzed for TSS and TIP. For samples collected via Isco in Ditch 1 only six samples were analyzed for TSS and four for turbidity.

Physicochemical Analyses

Samples were generally analyzed within 24 hours of arriving at the laboratory. Raw samples were shaken to resuspend sediment prior to analysis. Turbidity was analyzed following the Nephelometric Method 2130B (APHA, 1998) using a HACH 2100P portable turbidimeter. TSS was determined by filtration through glass filters (CG-B, <2 μm pore size) following method 2540 D (APHA, 1998). Depending upon the expected value, sample volume varied from 10-100 mL to prevent clogging. TIP was determined with a HACH DR 5000 spectrophotometer utilizing the HACH methods TNT 843, TNT 844, TNT 845 (depending upon concentration, total range: 0.05-20 mg/L PO_{4-}-P). Analyses using HACH methods followed protocols established in HACH (2008). Due to time constraints, turbidity and TIP were not measured on site as recommended.

Raw samples were filtered through 0.45 μm pore diameter nitrocellulose filters for analysis of DIP, NH_{3+}-N, and oxidized N species (NO_{x-}N). Prior to date 9/29/2011 a HACH DR 500 spectrophotometer was used to measure NH_{3+}-N (HACH TNT 830, range 0.015 – 2 mg/L NH_{3-}N); and DIP (HACH TNT 843). After 9/29/2011 all dissolved nutrient concentrations were determined with EPA equivalent methods using a Lachat QuickChem 8500 flow injection analyzer. Ammonia was determined using QuickChem method 10-107-06-1-J (range: 0.01 – 2 mg/L NH_{3+}-N). DIP was estimated using QuickChem method 10-115-01-1-A (range: 0.01 – 2 mg/L PO_{4-}-P). NO_x was determined using QuickChem method 10-107-04-1-0 (range: 0.05 – 10 mg/L NO_{x-}N). Nitrite was determined using QuickChem method 10-107-05-1-B (range: 14-70 μg/L NO_{2-}-N). NO_{3-} -N was calculated as the difference of $[NO_x] – [NO_{2-}]$. Only the calculated values for NO_{3-} -N are presented in the results section.

Data Analysis

Because data were non-normally distributed, non-parametric statistical analyses were used to discriminate among the various parameters. Due to the limited utility of non-parametric tests for determining interactions among multiple independent variables, a combination ordination, parametric statistics and visual examination of distributions were used to screen the data for potential interactions. In both grab samples and storm samples no differences were found based on sample station within a given ditch. Therefore, sample station was not considered as a factor in the subsequent analyses and all samples within a ditch were analyzed without respect to location. Likewise, although during some precipitation events the relative position of the storm sampler in the water column (top sampler versus bottom sampler) produced different values, the samples were not analyzed with respect to height, as there were no discernible trends in pollutant values in the samples.

NO_{3-} -N, DIP and NH_{3+}-N were initially analyzed using Kruskal-Wallace one-way analysis of variance to find differences among ditches and among different sampling methods (a = 0.1). Because particulate-related water quality parameters (turbidity, TSS, and TIP) were not necessarily all analyzed together on a given sample, it was necessary to analyze each individually, rather than as a set of dependent variables. Any significant effects were analyzed as pairwise comparisons using a two-sample Kolmogorov-Smirnov test (a = 0.1). This test was selected because it specifically compares the probability distribution between groups, rather than comparing central tendency and variance. Because of the large number of sampling dates relative to the overall number of samples collected and wide variability in the number of samples collected on a given date, sampling date was not analyzed. Both existing literature and visual examination of our data suggest, however, that date was among the most important factors influencing nonpoint source pollution. As the Kolmogorov-Smirnov test differentiates between groups based on the shape and range of the probability distribution, it was chosen as the most parsimonious test to compare among all dates. Isco samples were divided into first-flush (the initial hour, samples 1-6), and extended flows (hours 2-19, samples 7-24) and compared to fixed-height, passive storm samplers located at the outflow of Ditches 2 and 3.

Results

Summary data for all pollutants are listed in Table 3. These values are not weighted based on the number of samples collected or discharge. Both the sampling method and the ditch being sampled influenced the concentrations of pollutants in the water samples. There were an insufficient number of Isco samples in some ditches to compare all values among all sampling methods. Six sample dates included outflow concentrations determined from more than one sampling method within a given ditch. No differences were detected between methods in DIP or NH_{3+}-N concentrations for the limited number of samples available for comparison, although NH_{3+}-N was two times higher in grab samples than either method for collecting storm flows. NO_{3-}-N, on the other hand, was significantly lower in samples collected by storm samplers when compared to either Isco or grab samples. When comparing grab samples among ditches, Ditch 1, with the least amount of area in crop production, was generally lower in nonpoint source point pollution than other ditches except in DIP (Figure 4), which was higher, and TIP which was no different between ditches. During storm events, however, median particulate-related values were about double that of other ditches (Figure 5), with median TIP values around 4 ppm (not shown). When comparing the outflows of Ditches 2 and 3, which had the most complete data set, sampling method had no overall effect on dissolved nutrients (Figure 6). In 2011, grab samples yielded higher values for NO_{3-}-N than either storm sampling technique used; whereas in 2012 there were no differences. Particulate-related water quality values, in contrast, were strongly influenced by sampling method (Figure 5). Grab samples had the lowest values, followed by Isco samples, with storm samplers having the highest values. There were also differences between the initial hour of Isco sample and subsequent samples, with higher concentrations in samples from the first hour of storm events compared to subsequent samples (Figure 7). NO_{3-}-N tended to increase during a given storm event, but this trend was not pronounced enough to cause differences between the initial hour of Isco sampling and subsequent samples during the same storm event.

A large amount of variability was due to sampling date (Figures 8 & 9). NO_{3-}-N was episodically elevated during late winter and spring, as would be expected from fertilizer application, but there were no clear seasonal patterns. As the ditches were usually dry in the summer and fall, an adequate number of samples were not available to make comparisons.

Discussion

Ditch 1 differed in overall water quality from the other ditches, but not simply due to lower overall concentrations. These differences were likely primarily a result of different land use and drainage area. Lower NO_{3-}-N would be expected as the majority of the drainage area is not cropland. Additionally, the wetland area draining into the ditch would be expected to reduce NO_{3-}, while releasing orthophosphate into the water column. Given the presence of flow constrictions due to sedimentation in 2011, it is not altogether surprising to find elevated particulate pollutants.

Although turbidity and TSS were very high, they are not unheard off. In the northern Delta Region, Rebich et al. (2001) found mean sediment concentrations of 1492 mg/L in ditches draining row crops under conventional tillage. A six-year study near Clarksdale, MS recorded mean annual sediment concentrations in ditches ranging from approximately 2000-4800 mg/L (McDowell et al., 1989). Both studies utilized an automated pump system similar to the Isco samplers used in the present study. McDowell et al. (1989) utilized composites of ten-minute samples, rather than time-series samples. Given the sharp decline in sediment concentrations following the initial hour of runoff it is unclear whether the lower values in the present study are a result of site conditions or different sampling techniques. McDowell et al. (1989) also reported higher concentrations of P, which was mostly associated with sediment. In comparison, in data compiled by Shields et al. (2008, 2009) mean total P in watersheds of less than two square kilometers had values around 1 mg/L, comparable to the Isco samples in the present study.

In comparing dissolved nutrients, DIP at the Tchula Lake ditches was at the lower end of the range reported by McDowell et al. (1989) and slightly higher than reported by Schreiber (2001). Mean NH_{3+}, on the other hand, was higher than either previous study. Shields et al. (2008, 2009), in analyzing metadata collected from the 1980s-2000, found mean (nitrate+nitrite)-N (approximately equivalent to NO_{3-}-N in most row-crop drainages) concentrations of 1.7 mg/L at nineteen sites in the Delta Region of the Yazoo River. These data were comparable to concentrations measured in Delta ditches draining conventional tillage (Schreiber et al., 2001; McDowell, 1989), but lower than mean concentrations at the Tchula Lake site, regardless of sampling method. It is important to note that concentrations reported by Shields et al. (2008, 2009) were negatively correlated with drainage area, and in the smallest watersheds monitored had higher mean values. In a review of ditch monitoring studies in the Midwest Region of the United States, Blann et al. (2009) reported mean total N concentrations regularly exceeding 10 mg/L. As the previously cited studies in the Delta Region reported more than half of the total N as being particulate-bound, however, a large percentage of N in the water may be unaccounted for by only measuring dissolved species. Even compensating for this difference, the concentrations in the present study are still comparatively low in comparison to the Midwest.

This study highlights the importance of storm-related flows versus non-storm flows in a small agricultural watershed. Our results indicate that between storm events approximately 85-90% of inorganic P in the water column is DIP, whereas during storm flows only 1-5% is DIP. This trend was paralleled in the increased turbidity and suspended sediment observed during storm flows, as well as increased NO_{3-}-N concentrations. In contrast, NH_{3+}-N was essentially unaffected. Another interesting observation was the first-flush effect in these ditches with regard to sediment. During storm flows, TSS and associated values peaked in the initial hour, dropping off sharply afterward, indicating that the first-flush should be targeted for remediation of particulate-bound pollutants. NO_{3-}-N, on the other hand showed no such effect, with concentrations during some storm events still climbing after 19 hours of sampling. The differences observed between samples collected via storm samplers and those collected via Isco or grab sampling may be due to the specific timing of sample collection during the storm event, rather than any physical differences in sample collection. Given the importance of both N and P with regard to eutrophication, management efforts for decreasing nutrient transport from agriculture may need different strategies for monitoring particulate versus non-particulate pollutants in response to precipitation events.

Future Directions

The objective of this manuscript was to characterize water quality parameters of the Tchula Lake site and describe the implementation of drainage management practices on the site. A number of questions remain unanswered. Given the variability in concentrations among sampling dates and, likely precipitation, neither the effect of management practices nor seasonal effects were analyzed. These issues will be addressed in future publications and may require extended monitoring of the site. Information on farm management practices, such as fertilizer application, and hydrology data collected concurrently with water sampling will be incorporated into future analyses. These data are especially important in gauging the effectiveness of the water control structures on site, a topic that was not addressed in the present study. Beginning in August 2012, an undetermined number of sampling points in Tchula Lake will be incorporated into the routine grab sampling schedule to document any changes in water quality resulting from the implementation of drainage conservation structures.

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Table 1. Ditch Descriptions

Ditch #	Ditch Descriptive	Length (m)	Drainage Area (ha)	Predominant Soil types in drainage area	# weirs	# slotted pipes
1	Forest	2173	117	75% Alligator, Dowling, and Forestdale Soils	0	0
2	Main	1081	102	96% Alligator-Dowling Clays	4	7
3	Old Control	595	78.5	38% Dowling Clay, 25% Alligator Clay,	2	6
4	Laberto	1754	76	43% Alligator Clay, 9% Alligator Silty Clay Loam	4	12

Table 2. Number of samples analyzed for dissolved nutrients by sampling methods and ditch.

Ditch		Lachat Total	ISCO Total	Grab Total	Storm Total
1	Forest	102	49	24	29
2	Main	312	209	25	78
3	Old Control	298	230	27	41
4	Laberto	95	24	44	27

Table 3. Site Results Summary. All units are mg/L, except turbidity, which is NTU.

	Grab				Isco				Storm			
	Median	Mean	S.D.	N	Median	Mean	S.D.	N	Median	Mean	S.D.	N
TSS	188	336	679	162	562	803	985	274	3108	5314	7134	169
Turbidity	239	389	685	88	956	1550	1578	172	3490	5941	8764	115
TIP	.36	.51	.74	166	.89	1.23	1.21	439	1.29	4.34	8.25	173
DIP	.31	.08	.16	118	.04	.10	.19	489	.04	.09	.11	175
NH_3-	.13	.23	.33	118	.13	.26	.85	489	.15	.32	.61	175
NO_3+	.77	2.53	4.30	118	2.48	4.02	4.32	489	1.53	3.71	6.25	175

Figure 1. Aerial view of study site. Ditches are shown in blue, with the corresponding drainage areas outlined in red. Weirs are shown as red dots along the ditches. Tchula Lake is shown as a sinous white line at the southwest (bottom-left) and east (right).

Figure 2. Ditch 2 (Main ditch) following dredging and hydroseeding. A small in-channel floodplain is located ¾ of the way down the bank, characteristic of a 2-stage ditch.

Figure 3. Passive water control structures currently in place at the study site. A. Slotted weirs intercept swale inflows from adjacent fields, with a shallow basin to limit bed flow of sediment. B. Low-grade weirs slow storm water velocity, allowing sedimentation at discrete points along the ditch, and create intermittent pools between storm flows. A storm sampler array is visible immediately downstream of the weir.

Figure 4. Median concentations (mg/L) of dissolved nutrients in grab samples.

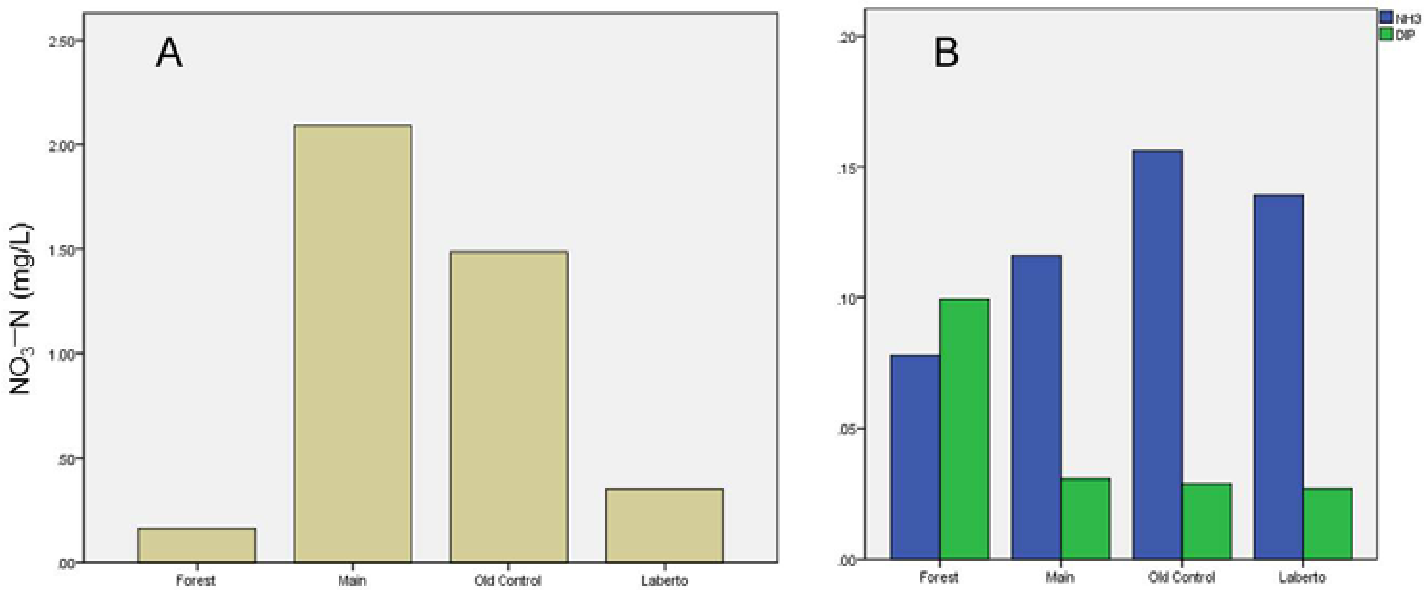

Figure 5. Summary of median TSS and turbidity across ditches using different sampling methods. A. Grab samples. B. Isco samples. C. Stormsamples. In Ditch 1 (Forest) only 6 samples were used to determine TSS and 4 for turbidity in Isco samples. All other bars represent a minimum of 19 samples.

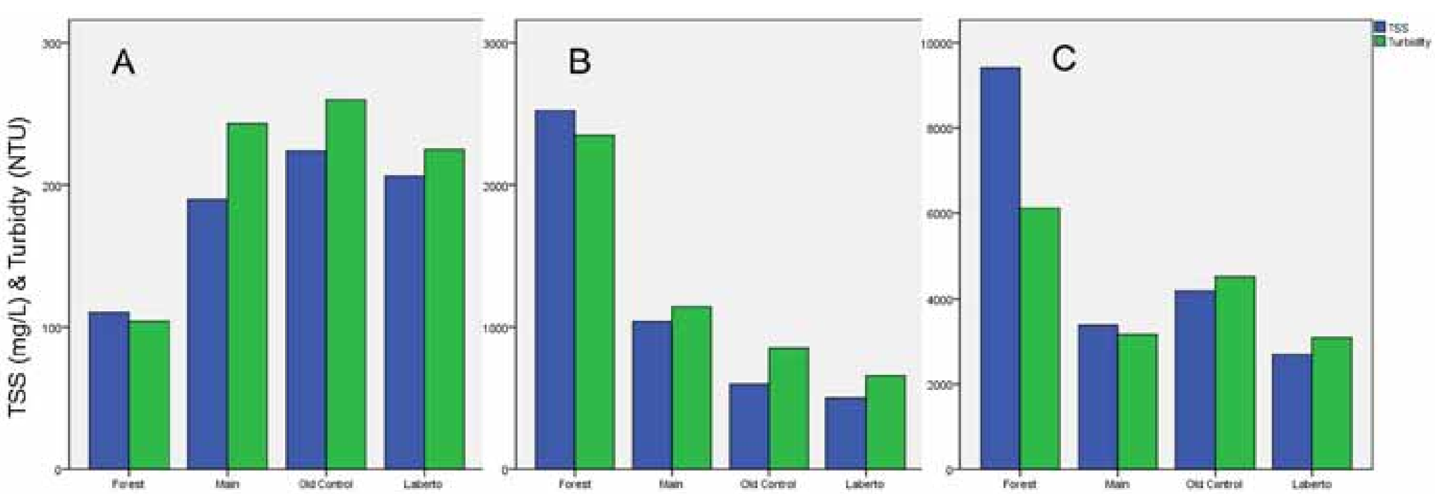

Figure 6. Summary of Median NO3- -N concentrations at outflows of Ditch 2 and Ditch 3.

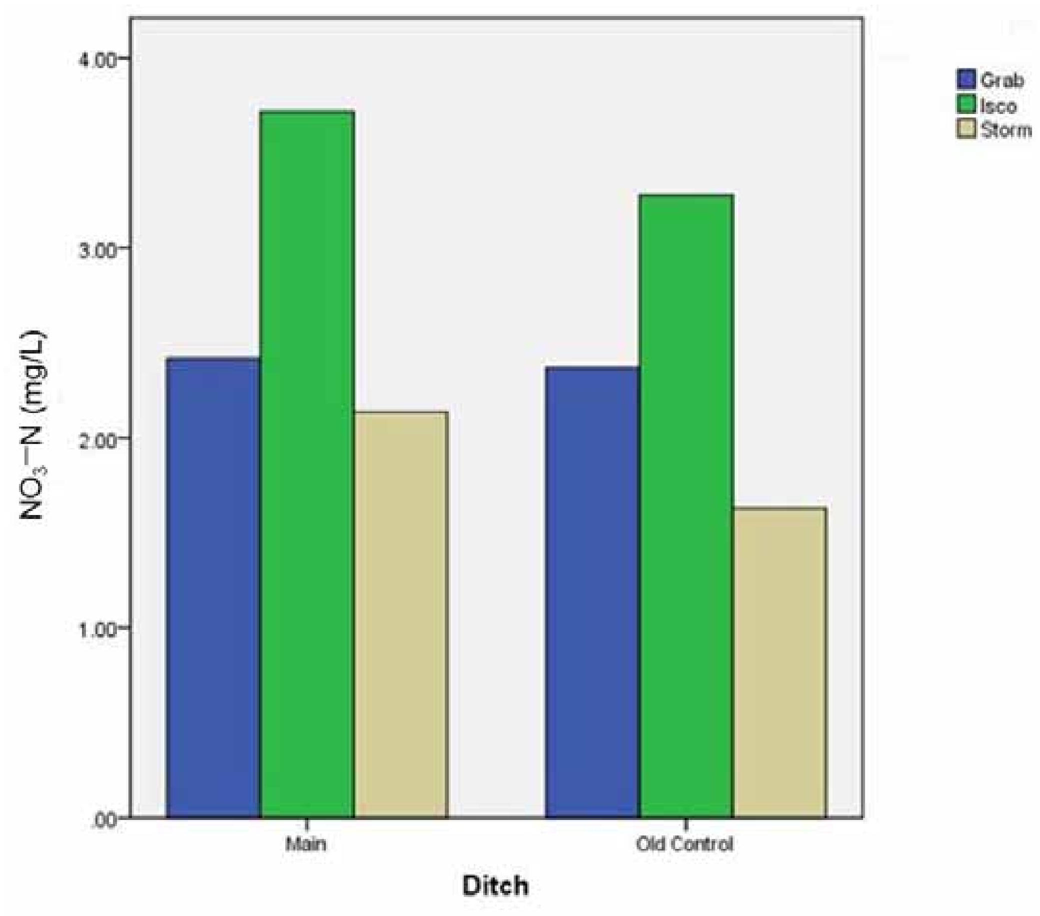

Figure 7. TIP and TSS concentrations (mg/L) in Ditch 2 and 3 by sample number. The first six samples (left of blue line) represent the first hour of storm flow at 10-minute intervals. Subsequent samples are at hourly intervals.

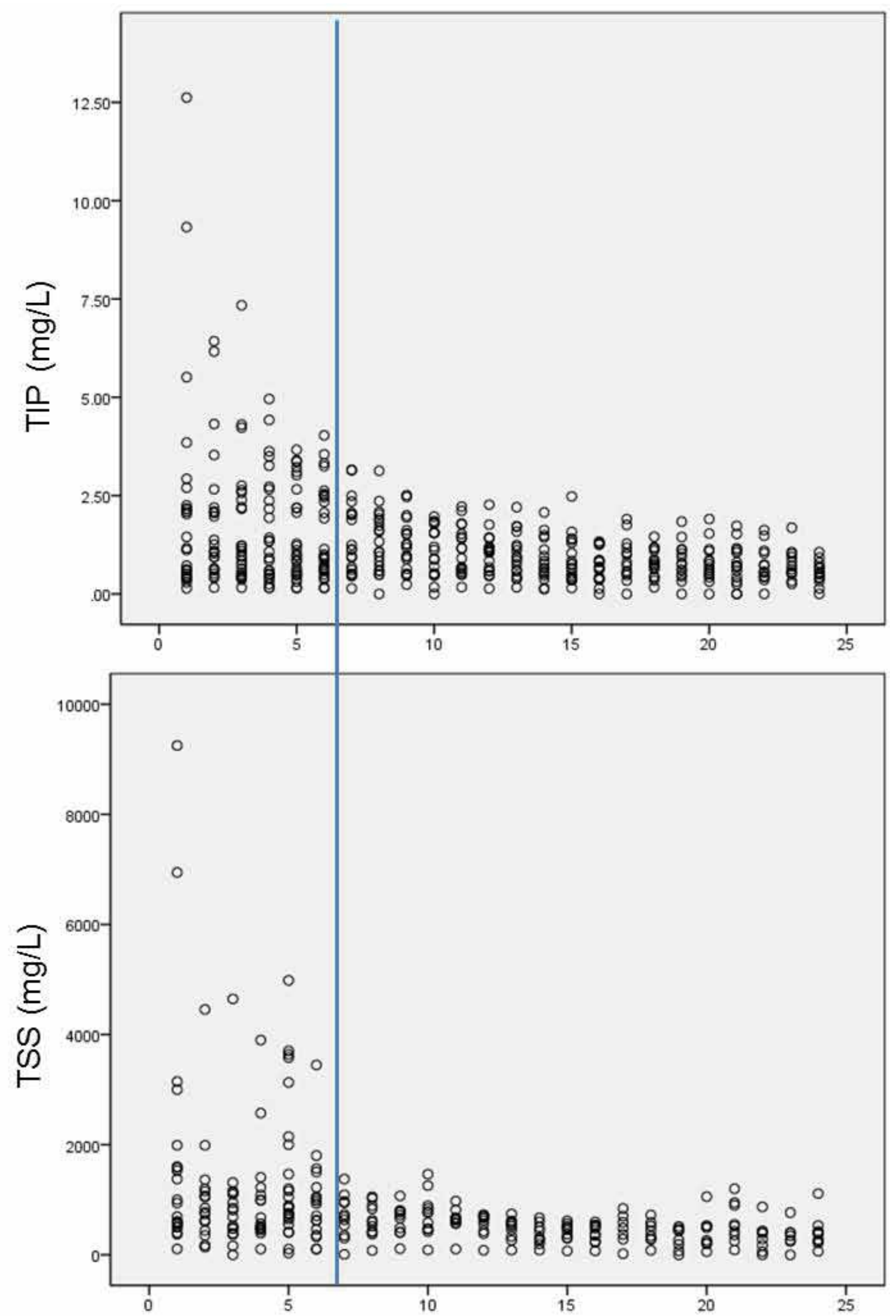

Figure 8. Median particulate pollutants by date and sampling method. A. Grab samples. B. Isco samples. C. Stormsamples. Turbidity values are NTU. TSS is mg/L. TIP is shown in µg/L, rather than mg/L as listed in the text and tables.

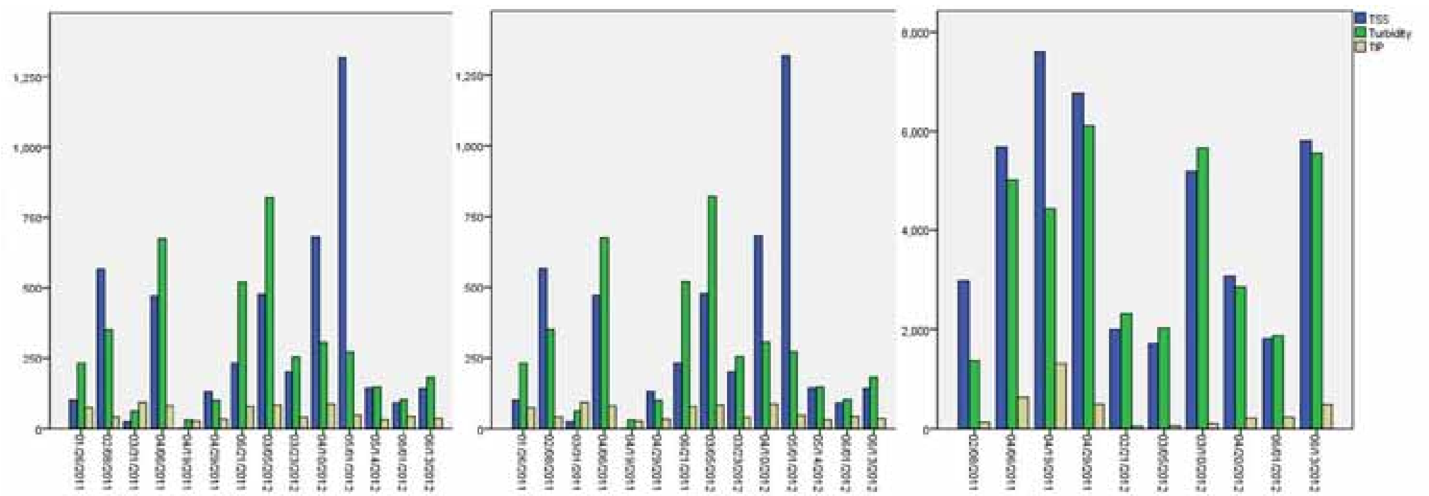

Figure 9. Median concentrations of dissolved nutrients (mg/L) by date and sample method. A. Grab samples. B. Isco samples. C. Stormsamples. Samples collected on 12/8/2011 and 12/9/2011 were for a single storm event.