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ABSTRACT. *In February 2001, the Texas Commission on Environmental Quality (TCEQ) adopted a Total Maximum Daily Load (TMDL) for soluble reactive phosphorus (SRP) along the North Bosque River. Within this TMDL, dairy waste application fields were identified as the major nonpoint-source contribution of nutrients. In September 2000, a manure composting program was initiated that resulted in about 500,000 metric tons of dairy manure being hauled to composting facilities and exported from the watershed through December 2004. To evaluate the impact of the manure composting program on stream water quality, storm event mean concentrations of nutrients and total suspended solids were compared before and after the start of the program at seven stream sites representing a range of land uses and levels of participation in the program. Data were analyzed as a "before/after" monitoring design using analysis of covariance (ANCOVA) with flow as the covariate and Wilcoxon rank sum (WRS) procedures with flow-adjusted data because flow was positively correlated to concentration. Although the manure composting program has only been in place about four years, water quality appeared to be improving at sites with the highest levels of manure removed per cow and watershed area. At these sites, SRP concentrations decreased from 19% to 23%. Significant decreases in SRP were not seen at stream sites with lower levels of manure hauled off, normalized on a per area and cow basis, indicating that the level of participation in the manure composting program might be a major determinant of the level of impact.*

Keywords. *Compost, Dairy waste, Manure, Phosphorus, TMDL, Water quality.*

In February 2001, the Texas Commission on Environmental Quality (TCEQ, formerly the Texas Natural Resource Conservation Commission) adopted a Total Maximum Daily Load (TMDL) for soluble reactive phosphorus (SRP) for segments 1226 and 1255 of the North Bosque River (TNRCC, 2001; fig. 1). This TMDL and its associated implementation plan to improve water quality were initiated in response to excessive algal growth associated with elevated nutrient levels. Through environmental studies, SRP was identified as the nutrient controlling the growth of algae (Kiesling et al., 2001).

To obtain desired reductions in algal growth, the TMDL goal stipulates on average a 50% reduction in soluble P concentrations and loadings along the North Bosque River (TNRCC, 2001). Within the TMDL process, dairy waste application fields were identified as the major nonpoint-source contributor. The headwaters of the North Bosque River are located almost entirely within Erath County, the primary milk-producing county in Texas (USDA-AMS, 2004). As of October 2002, 78 dairies with more than 40,000 milking cows were active in the North Bosque River watershed.

Dairy manure is generally disposed of through land application. While land application is a beneficial use of manure nutrients, these nutrients can potentially be transported to streams via rainfall runoff. In September 2000, the Texas State Soil and Water Conservation Board (TSSWCB) initiated the Dairy Manure Export Support (DMES) project to export dairy manure from the North Bosque River watershed (TSSWCB, 2005). The DMES project provides incentives to haulers to transport manure from dairies to composting facilities in conjunction with TCEQ's Composted Manure Incentive Project (CMIP).

Through CMIP, TCEQ is responsible for providing technical assistance to composters and ensuring that manure is properly processed and contained at composting facilities (TCEQ, 2005). Only manure hauled to composting facilities participating in CMIP is eligible for DMES hauling reimbursement. In turn, the compost can then be hauled to other watersheds as a beneficial soil amendment. CMIP also provides rebates to Texas state agencies that use manure compost received through the DMES project. For example, the Texas Department of Transportation (TxDOT) uses the dairy manure compost for roadside revegetation projects. Individual composting facilities are also developing markets for compost as a beneficial amendment for gardening and turfgrass production. Jointly, these two projects, DMES and CMIP, comprise a comprehensive manure composting program for the North Bosque River watershed. The goal of these two projects is to reduce nutrient loading from conventional land application practices through the relocation of manure outside the watershed.

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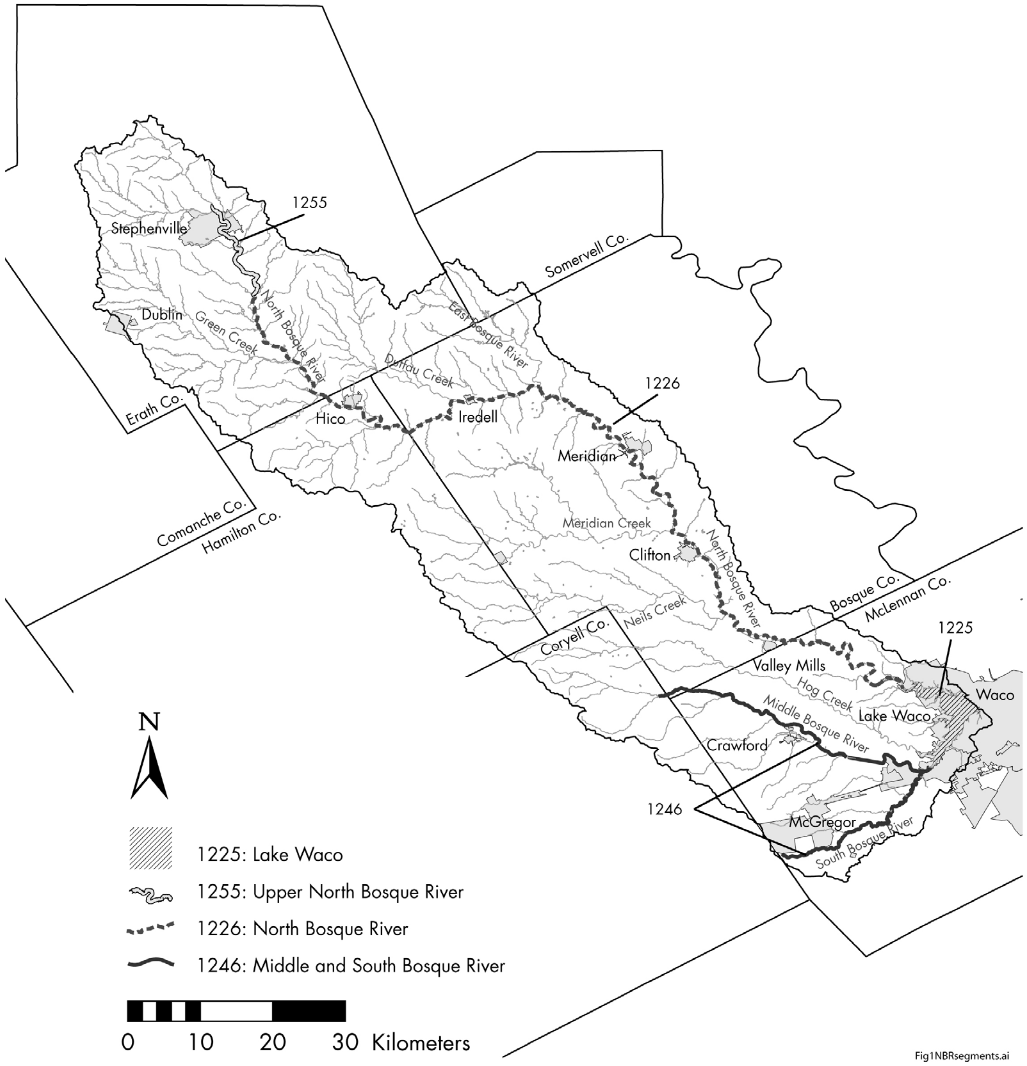

Figure 1. Classified stream segments within the Bosque River watershed.

Almost 50% of all dairies participated at some level in the manure composting program, leading to the haul-off of about 500,000 metric tons of dairy manure from within the North Bosque River watershed between November 2000 and December 2004 according to the DMES project records. This represents about 50% of the manure produced in that time period, assuming that (1) a dairy cow produces 7.6 kg of solid manure per day on a dry matter basis (*ASAE Standards,* 2005), (2) the manure has a moisture content of 50% when transported to composting facilities (NRCS, 2003), and (3) an average of 40,000 dairy cows were present in the watershed.

While the program has had a fairly large level of participation overall, it is not known whether improvements in stream water quality will be readily observable. Several factors determine the success of nutrient management practices on stream water quality within a watershed. These factors include management effectiveness (Meals, 1992; Bottcher et al., 1995), land use type (Wang, 2001; Fisher et al., 2000), chemical and hydrologic factors (Sharpley et al., 1999; Moog and Whiting, 2002), farmer participation (Meals, 1992), and the measurement scale (Gburek et al., 2000; Dougherty et al., 2004; Harmel et al., 2004). In small plot- or field-scale studies, most of these factors can be controlled and results can be obtained within a short time period. On the watershed scale, it is often difficult to control these confounding factors, and changes in water quality generally occur more gradually. Changes in water quality associated with nonpoint-source contributions often lag changes in land management because of residual impacts from past management practices (Clausen et al., 1992; Meals, 1992, 1996; Nikolaidis et al., 1998). The length of this time lag can vary greatly, particularly with regard to P, based on whether the soil itself is acting as a sink or source of P (Sharpley, 1995; Sharpley and Rekolainen, 1997).

The question remaining is whether this large amount of dairy manure that has been moved to composting facilities rather than being land applied has resulted in measurable improvements in water quality. The specific objectives of this research were to determine if improvements in water quality are occurring in the watershed and, if so, can these improvements be associated with the haul-off of dairy manure to composting facilities.

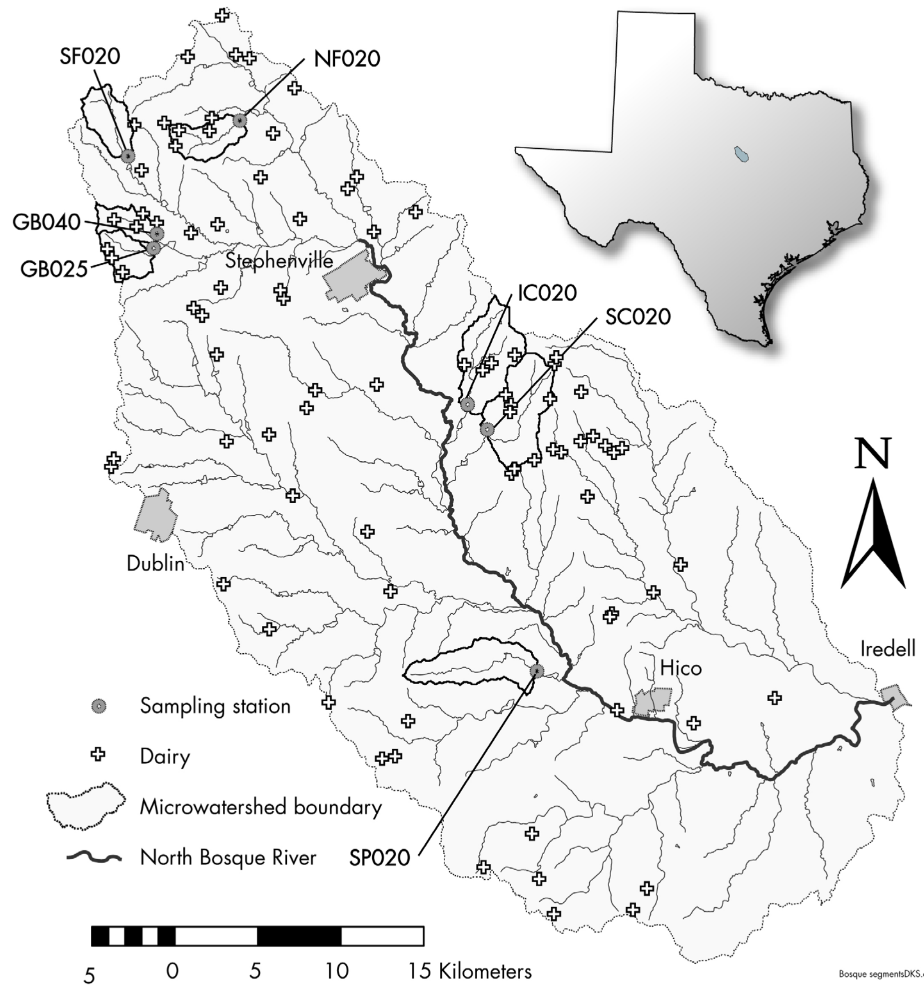

Figure 2. Location of sampling sites and watersheds. Dairy locations are shown for reference.

Materials and Methods

Site Characteristics

The North Bosque River watershed located in central Texas extends about 180 river km (110 river miles) from Stephenville to Lake Waco (fig. 1). Seven sampling sites located in the upper portion of the North Bosque River watershed above Iredell (GB025, GB040, IC020, NF020, SC020, SF020, and SP020) were used in this study (fig. 2).

These headwater sampling sites were selected because they represent the range of rural land uses within the watershed (table 1) and have a fairly long monitoring history (table 2). All sites were maintained and operated by the Texas Institute for Applied Environmental Research (TIAER) at Tarleton State University, under contract with the TSSWCB as part of a Clean Water Act Section 319(h) Nonpoint-Source Pollution Control Program project (TIAER, 2004). Because monitoring was conducted under a variety of different projects, the monitoring period varied between sites (table 2). Generally, monitoring continued through December 2004, except at site SF020. Monitoring at site SF020 was discontinued in January 2003 at the request of the private landowner. At sites IC020, SC020, and SP020, monitoring was sus–

Table 1. Estimated land use and watershed area above sampling sites (adapted from Adams et al., 2005).

Site	Wood and Range (%)	Pasture (%)	Cropland (%)	Dairy Waste Application Fields (%)	Urban (%)	Other (%)	Total Area (ha)	Estimated Milking Herd Size[a]
NF020[b]	29.7	14.2	3.3	52.6	0.1	0.1	800	1500
GB040	21.1	42.8	4.9	30.2	0.7	0.1	540	2100
GB025	29.5	13.5	0.6	55.9	0.5	0.0	660	2750
IC020	64.9	16.8	6.1	11.8	0.3	0.0	1,740	1650
SC020	68.7	9.4	1.4	20.0	0.1	0.4	1,900	420
SF020	96.4	2.4	0.8	0.2	0.1	0.1	850	0
SP020	82.6	12.0	5.2	0.0	0.1	0.1	1,560	0

[a] Estimated milking herd size represents the average from TCEQ annual inspection numbers for 2000 through 2004. When inspected numbers were not available, an estimate was used assuming 70% of the permitted herd size, except at SC020. Within the watershed above SC020, all three dairies were non-permitted facilities with less than 200 head. A maximum of 200 head was assumed for these three facilities with an estimated herd size of 140 head.

[b] About 8 ha (20 ac) or about 1% of the watershed area above NF020 is permitted for septic disposal and was classified with dairy waste application fields.

Table 2. Monitoring period by sampling site.

Site	Monitoring Period
NF020	1993 – 2004
GB040	1997 – 2004
GB025	1997 – 2004
IC020	1993 – 2004[a]
SC020	1993 – 2004[a]
SF020	1993 – 2003
SP020	1993 – 2004[a]

[a] Monitoring suspended March 1998 through May 2001.

pended from March 1998 through May 2001 due to changes in monitoring priorities.

Streamflow at these small headwater sampling sites is highly intermittent and generally associated with rainfall runoff. These stream sites are often dry or pooled and not flowing during the summer and early fall. These rural watersheds do not have significant point-source contributions; thus, water quality impacts are primarily from nonpoint sources, which generally vary with the degree of intensive agriculture above each site (McFarland and Hauck, 1999). Of the seven sites, GB025 and NF020 have a relatively high potential for impact from dairy waste application fields. In contrast, SF020 and SP020 are dominated by range and wood land and represent relatively unimpacted sites (table 1). Sites GB040, IC020, and SC020 have moderate potential for impact from dairy waste application. Pasture within these watersheds consists primarily of coastal bermudagrass (*Cynodon dactylon* (L.) Pers Coastal). Cropland is usually double-cropped with sorghum (*Sorghum bicolor*) and winter wheat (*Triticum* spp.). Dairy waste is generally applied to pasture or cropland. Dairy application fields are represented as a separate land use category based on information obtained from dairy permits and dairy waste management plans on record with the TCEQ as of May 2000.

Records obtained from the DMES project on manure hauled to composting facilities were summarized by watershed above the sampling site and normalized based on the number of cows and watershed area (fig. 3). The most manure hauled per cow population and watershed area occurred above sites NF020, GB040, and GB025 (fig. 3). It was expected that the sampling sites with the greatest manure export per cow and unit area would show the greatest improvement in water quality, especially with respect to SRP. Moderate impacts due to the manure composting program were expected at site IC020 with a lower level of participation in the program on a per cow and area basis. At SC020, SF020, and SP020, no impact was expected due to the manure composting program. Although there are three dairies in the watershed above site SC020 and one with waste application fields in the watershed above site SF020, none of these dairies had manure hauled to composting facilities. The watershed area above site SP020 contains no dairy operations or waste application fields, so no impact was expected from the manure composting program.

Data Collection and Laboratory Methods

The data collection in this study focused on nonpoint-source nutrient contributions in storm events. Samples were collected during each storm event using automated sampling equipment consisting of an Isco 4230 or 3230 bubbler-type

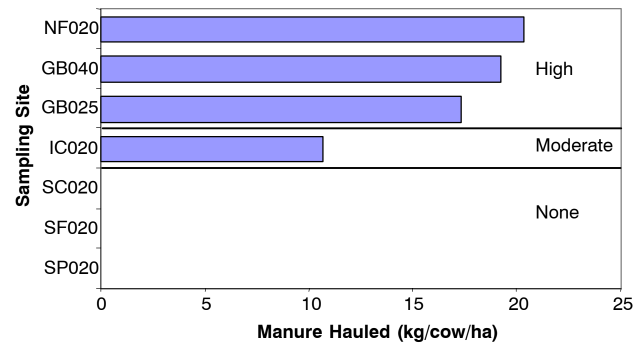

Figure 3. Manure hauled (Nov. 2000 to Dec. 2004) normalized by watershed area and average number of cows above the sampling sites. High, Moderate, and None represent expected composting impact.

flowmeter and an Isco 3700 sampler. The Isco flowmeters were programmed to record water level at 5 min intervals and to initiate sample retrieval when a rise of 4 cm above the bubbler datum was registered. Once activated, the samplers retrieved 1 L samples generally using the following sampling sequence: initial sample, three samples at 1 h intervals, four samples at 2 h intervals, and all remaining samples at 6 h intervals. Samples collected prior to June 1997 were generally analyzed individually as collected. Due to cost and staffing issues after June 1997, most storm samples were flow composited (subsamples with volume proportional to the flow volume were withdrawn and placed in a single bottle) on a daily basis prior to laboratory analysis. Stage-discharge relationships were developed for each site from manual wading-type flow measurements taken at various water level conditions following USGS methods (Buchanan and Somers, 1969). Stage-discharge relationships for stages that permitted safe wading were extrapolated using the cross-sectional area and a least-squares relationship of average stream velocity to the log of water level. Constituents were analyzed using USEPA-approved methods (USEPA, 1983) with slight modifications for the analysis of total P and TKN. Total P was analyzed using colorimetric automated block digestion method 365.4, and TKN was analyzed using colorimetric automated phenate method 351.2. Both total P and TKN methods were modified to use copper sulfate as the catalyst instead of mercuric oxide. SRP was analyzed on sample filtrate (0.45 μ membrane) using colorimetric ascorbic acid method 365.2. Dissolved NO_2-N+NO_3-N was analyzed using colormetric automated cadmium reduction method 353.2, and dissolved NH_3-N was analyzed using semi-automated colorimetry method 350.1. TSS was analyzed as non-filterable residue using gravimetric method 160.2 with drying at 103°C to 105°C.

Laboratory method detection limits (MDLs) or left censored data below which the laboratory is unable to differentiate from zero were entered into the database as one-half the MDL following recommendations by Gilliom and Helsel (1986) and Ward et al. (1988). Values below the MDL can cause problems with statistical evaluation, especially when detection limits change. In TIAER's laboratory, MDLs are updated about once every six months. In preparing data sets for analysis, the maximum MDL was identified for each site by constituent. For consistency, all values in the database below half the maximum MDL were set equal to half the maximum MDL.

Data Set Construction

Event mean concentrations (EMCs) were calculated for each storm event by accumulating the mass via rectangular integration using a midpoint rule to associate concentration with streamflow (Stein, 1977). The 5 min stage readings were used as the minimum measurement interval and multiplied by 300 s to obtain the flow for each 5 min interval. The flow associated with each 5 min interval was multiplied by the associated water quality concentration and summed across the event to calculate total constituent loadings. Total constituent loadings were divided by total storm volume to calculate EMCs.

Preliminary analyses of the data at sites NF020, GB025, GB040, and IC020, indicated that certain runoff events may have been impacted by effluent discharges from dairy retention control structures rather than solely from nonpoint-source runoff. In most cases, this could not be verified. However, to isolate the impact of the manure composting program, it was important that such potential contributions from other sources be removed. Consequently, a separate data set was constructed, deleting data points suspected to be impacted by effluent discharges. Data points were deleted if they had uncharacteristically high NH_3-N concentrations (>5.0 mg/ L) because wastewater effluent from dairies is typically associated with high ammonia values. This reduced data set was then analyzed and compared to the full data set including all storm events. Some differences were observed in the results between the full and reduced data sets (Bekele and McFarland, 2004a); therefore, only results from reduced data set modified to remove the potential impact from effluent discharges is presented.

Statistical Methods

Evaluation of changes in water quality due to the manure composting program was based on detection of a step trend. Step trend procedures are used in two cases (Helsel and Hirsch, 1992). The first case is when the record being analyzed is broken into two distinct periods with a relatively long time gap between them. The other case is when a known event likely to have resulted in a change in water quality (e.g., the initiation of the manure composting project) occurred at a specific time during the record. The record can, thus, be divided into a "before" and "after" period. For our data, records before the start of the manure composting program (November 2000) were designated "before," while records after November 2000 were designated "after." The data were then analyzed as a "before/after" monitoring design (Grabow et al., 1999; Smith, 2002) using the analysis of covariance (ANCOVA) and the nonparametric Wilcoxon rank sum (WRS) procedures (SAS, 2000).

In the ANCOVA, average streamflow for each event was used as the covariate. The ANCOVA consists of multiple steps determining the statistical significance (1) of the regression equations relating streamflow and concentration from the two monitoring periods, (2) of the equality of these regression slopes, and (3) of the difference between the intercepts of the regressions from the two monitoring periods (Littell et al., 1996; NRCS, 1997). ANCOVA was performed on the natural log-transformed data to satisfy the assumptions of the homogeneity of variance and the homogeneity of regression (Littell et al., 1996). Results from ANCOVA are considered flow-adjusted since ANCOVA allows obtaining estimates of differences among treatment level means (for the before and after periods) that would occur if all the concentrations have the same streamflow (Keppel, 1991).

In the WRS analysis, data were flow-adjusted prior to analysis using locally weighted regression and smoothing scatterplots (LOWESS) with a smoothing coefficient of 0.5 (Helsel and Hirsh, 1992; Bekele and McFarland, 2004b). The residuals from LOWESS regression were then used in the WRS test. This test is based on the assumption that if the regressions represent the variability due to streamflow, then a difference in the regression residuals could be attributed directly to a difference due to the manure composting program (Helsel and Hirsh, 1992).

Both parametric and nonparametric procedures were implemented because at one site (SC020) the assumptions associated with the ANCOVA could not be fully met. In addition, the application of both parametric and nonparametric methods on the same data set is considered useful because it provides assurance in the interpretation of results (NRCS, 1997). A step trend confirmed by both analyses was judged more meaningful than one indicated by only one test. All statistical significance was judged at an $\alpha = 0.10$ probability level.

Results and Discussion

Water Quality Before/After Results

To present an overview of the water quality at each site, summary statistics for the original EMC data (unadjusted for flow variations and without log transformation) from the two monitoring periods are presented in table 3. For reference, the sites are listed in order from highest to lowest expected impact associated with the manure composting program, as indicated in figure 3. These summary statistics should not be used for statistical tests of differences in water quality at a site between periods without flow adjustment because flow can greatly influence concentrations (Helsel and Hirsh, 1992). These summary statistics are included for general comparison of water quality and the impacts of land uses in the watershed above each site (table 1). Both before and after initiation of the manure composting program, sampling sites with watershed areas containing a large percentage of land area comprised of dairy waste application fields (GB025 and NF020) consistently showed higher SRP and total P concentrations. Whereas sampling sites with few or no dairies in their watershed (SP020 and SF020) had the lowest SRP and total P concentrations in storm events. The general pattern shown for SRP and total P concentrations also occurred for TKN and to a lesser degree for NH_3-N, but not for NO_2-N+NO_3-N or TSS (table 3). The highest average NO_2-N+NO_3-N and TSS concentrations occurred at site GB040. Site GB040 has a moderately high percentage of dairy waste application fields in its watershed (30%), but it also has a history of cows watering in the creek. The direct impact from cows watering in the creek near GB040 is probably a factor in the relatively high NO_2-N+NO_3-N and TSS concentrations at this site.

Although the basic statistics have not been flow-adjusted, median values of SRP generally decreased between the "before" and "after" periods, except at GB025. As noted previously, these changes in median EMCs should not be used directly to indicate changes between the "before" and "after" periods because of the confounding effect of flow

Table 3. Storm event summary statistics without flow adjustment and without log transformation before and after initiation of the manure composting program.

Site, and Expected Composting Impact	Attribute	Number of Events		Mean		Median		Standard Deviation	
		Before	After	Before	After	Before	After	Before	After
NF020, High	Flow (m^3/s)	82	52	0.18	0.17	0.07	0.10	0.31	0.20
	SRP (mg/L)	82	52	1.11	1.01	1.06	0.99	0.81	0.73
	Total P (mg/L)	82	52	2.14	2.37	1.97	1.85	1.17	1.76
	TSS (mg/L)	82	52	1261	960	619	434	2038	2097
	NO_2-N+NO_3-N (mg/L)	82	52	5.78	6.10	4.73	3.83	4.57	5.00
	NH_3-N (mg/L)	82	52	0.53	0.39	0.24	0.19	0.75	0.48
	TKN (mg/L)	82	52	1.35	1.20	1.05	0.94	1.19	0.87
GB040, High	Flow (m^3/s)	28	51	0.02	0.07	0.01	0.03	0.02	0.09
	SRP (mg/L)	28	51	1.28	1.02	1.11	1.02	0.77	0.43
	Total P (mg/L)	28	51	3.21	2.84	2.73	2.45	2.37	1.55
	TSS (mg/L)	28	51	1100	2535	660	644	1302	6375
	NO_2-N+NO_3-N (mg/L)	28	51	9.00	8.43	9.09	6.66	5.98	6.09
	NH_3-N (mg/L)	28	51	1.00	0.68	0.57	0.42	1.11	0.76
	TKN (mg/L)	28	51	5.80	4.81	3.97	2.69	5.34	6.30
GB025, High	Flow (m^3/s)	38	45	0.01	0.06	0.00	0.02	0.02	0.09
	SRP (mg/L)	38	45	1.21	1.51	0.94	1.42	0.83	1.05
	Total P (mg/L)	38	45	3.94	3.39	3.17	3.40	2.50	1.34
	TSS (mg/L)	37	45	3190	2303	1212	780	5004	3334
	NO_2-N+NO_3-N (mg/L)	38	45	12.92	8.87	8.11	6.68	13.07	6.06
	NH_3-N (mg/L)	38	45	0.46	0.50	0.25	0.28	0.67	0.68
	TKN (mg/L)	38	45	1.36	1.64	1.02	1.15	1.32	1.51
IC020, Moderate	Flow (m^3/s)	60	45	0.24	0.12	0.12	0.04	0.31	0.20
	SRP (mg/L)	60	45	0.70	0.68	0.65	0.61	0.38	0.43
	Total P (mg/L)	60	45	1.20	1.29	1.20	1.24	0.62	0.65
	TSS (mg/L)	60	45	232	323	174	189	251	336
	NO_2-N+NO_3-N (mg/L)	60	45	3.27	3.83	2.95	3.63	1.76	1.78
	NH_3-N (mg/L)	60	45	0.17	0.38	0.12	0.20	0.25	0.65
	TKN (mg/L)	60	45	1.11	1.42	0.90	1.32	0.81	0.90
SC020, None	Flow (m^3/s)	52	40	0.26	0.13	0.19	0.02	0.31	0.32
	SRP (mg/L)	52	40	0.15	0.19	0.14	0.13	0.12	0.18
	Total P (mg/L)	52	40	0.35	0.52	0.34	0.39	0.20	0.43
	TSS (mg/L)	52	40	112	208	64	106	142	312
	NO_2-N+NO_3-N (mg/L)	52	40	1.37	1.98	1.37	1.67	0.64	1.42
	NH_3-N (mg/L)	52	40	0.15	0.16	0.10	0.10	0.14	0.16
	TKN (mg/L)	52	40	0.42	0.60	0.39	0.41	0.21	0.51
SF020, None	Flow (m^3/s)	95	27	0.12	0.07	0.04	0.01	0.19	0.12
	SRP (mg/L)	95	27	0.04	0.04	0.03	0.03	0.04	0.05
	Total P (mg/L)	95	27	0.23	0.26	0.19	0.25	0.16	0.14
	TSS (mg/L)	95	27	220	382	124	216	298	631
	NO_2-N+NO_3-N (mg/L)	95	27	0.24	0.45	0.17	0.39	0.26	0.24
	NH_3-N (mg/L)	95	27	0.17	0.14	0.11	0.09	0.18	0.13
	TKN (mg/L)	95	27	1.41	1.89	1.28	1.78	0.73	0.93
SP020, None	Flow (m^3/s)	61	53	0.35	0.12	0.09	0.01	0.72	0.25
	SRP (mg/L)	61	53	0.04	0.02	0.02	0.01	0.05	0.04
	Total P (mg/L)	61	53	0.14	0.14	0.11	0.10	0.09	0.10
	TSS (mg/L)	61	53	56	75	16	20	84	132
	NO_2-N+NO_3-N (mg/L)	61	53	0.68	0.68	0.53	0.42	0.44	0.48
	NH_3-N (mg/L)	61	53	0.09	0.03	0.06	0.03	0.09	0.03
	TKN (mg/L)	61	53	0.10	0.09	0.05	0.04	0.12	0.09

variations on storm concentrations. Streamflow varied greatly between the two monitoring periods, as presented for GB025 (fig. 4).

The significant effect of stream flow variation on concentration can be seen by comparing results obtained from data adjusted for flow (table 4) and data unadjusted for flow (table 3). For example, a decrease in flow-adjusted EMCs for mean SRP was indicated at GB025, while median and mean EMCs for unadjusted data indicated an increase. The three sites (NF020, GB040, and GB025) with a high expected impact from the manure composting program based on the amount of compost haul-off (fig. 3) experienced significant decreases in SRP (table 4). No significant changes in SRP concentrations were noted at site IC020, which was moderately impacted by the manure composting program, or at sites SC020 or SF020, with no influence from the manure composting program. Of note, only the nonparametric WRS test was used for data from site SC020, since the flow-

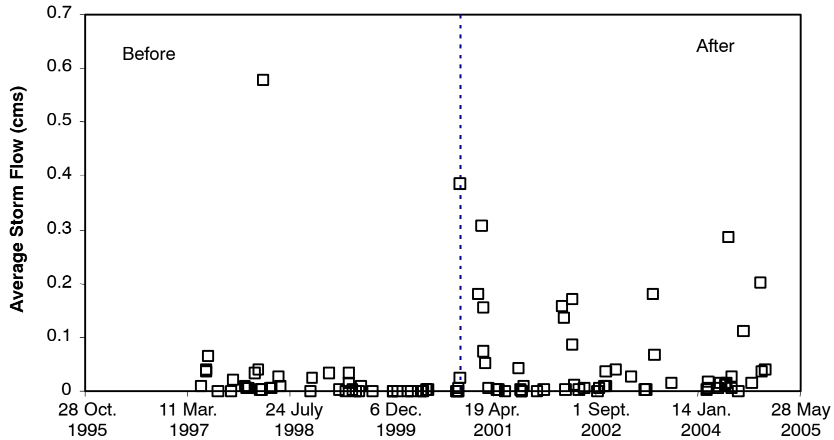

Figure 4. Event mean flows at site GB025. Dashed vertical line divides monitoring into periods before and after initiation of the manure composting program.

concentration relationship significantly changed during the study period for this site, thus violating the assumption of ANCOVA. In contrast, significant reductions in SRP were observed at site SP020, a least impacted site with no dairies in its watershed. It is suspected that improvements in laboratory precision for SRP concentrations played a role in the detection of significant decreases in low storm SRP concentrations at SP020 (table 3). The laboratory met all applicable quality assurance and control measures over the entire study. However, beginning in 2003, new instrumentation was implemented in the lab for the analysis of SRP, causing a demonstrated improvement in precision, particularly at low concentrations. Although this increase in laboratory precision is one possible factor in the decrease in SRP concentrations at SP020, other differences, such as weather conditions and land use patterns, between the two time periods cannot be ruled out.

Regardless of the cause, the absolute decrease at SP020 was much smaller than the absolute decreases noted at sites GB025, GB040, and NF020 (table 5). To quantify differences between the two time periods, the natural log transformed mean values from the ANCOVA were back transformed into their original units (table 5). At sites NF020, GB040, and GB025 where the highest potential impact from the manure composting program was expected, absolute decreases in EMCs of SRP ranged from 0.15 to 0.26 mg/L, while relative percent decreases varied from 19% to 23%. In contrast, SP020 showed an absolute decrease in EMC of SRP of 0.006 mg/L, representing a relative decrease of almost 29% during the time period of the manure composting program. At site IC020, a site at which a moderate impact from the manure composting program was expected, a potential but nonsignificant increase in EMCs of SRP was noted. Sites SC020 and SF020, where no impact from the manure composting program was expected, both showed a small but nonsignificant decrease in EMCs of SRP.

Table 4. P-values from analysis of covariance (ANCOVA) and Wilcoxon rank sum (WRS) comparing event mean concentrations before and after the start of the manure composting program. Up and down arrows indicate significant (α = 0.10) increases and decreases, respectively, in storm water quality.

Site	Expected Composting Impact	Analysis	SRP	Total P	TSS	NO_2-N +NO_3-N	NH_3-N	TKN
NF020	High	ANCOVA	0.125	0.981	0.062 ↓	0.223	0.565	0.726
		WRS	0.013 ↓	0.163	0.047 ↓	0.090 ↓	0.178	0.150
GB040	High	ANCOVA	0.035 ↓	0.597	0.308	0.574	0.066 ↓	0.440
		WRS	0.009 ↓	0.089 ↓	0.405	0.211	0.059 ↓	0.052 ↓
GB025	High	ANCOVA	0.122	0.524	0.845	0.851	0.506	0.873
		WRS	0.090 ↓	0.411	0.369	0.245	0.130	0.476
IC020	Moderate	ANCOVA	0.404	0.008 ↑	0.000 ↑	0.001 ↑	0.000 ↑	0.001 ↑
		WRS	0.190	0.002 ↑	0 .001 ↑	0.000 ↑	0.001 ↑	0.001 ↑
SC020[a]	None	ANCOVA	na	na	na	na	na	na
		WRS	0.294	0.034 ↑	0.017 ↑	0.176	0.441	0.012 ↑
SF020	None	ANCOVA	0.774	0.331	0.031 ↑	0.000 ↑	0.402	0.056 ↑
		WRS	0.136	0.153	0.059 ↑	0.001 ↑	0.135	0.123
SP020	None	ANCOVA	0.060 ↓	0.152	0.044 ↑	0.245	0.000 ↓	0.192
		WRS	0.016 ↓	0.124	0.027 ↑	0.120	0.000 ↓	0.333

[a] ANCOVA not performed for SC020 because the flow-concentration relationship significantly changed during the study period. Only the nonparametric Wilcoxon rank sum test was used.

Table 5. Estimated change (%) in flow-adjusted mean SRP concentrations before and after the implementation of the manure composting program.

Site	Expected Composting Impact	SRP[a] (mg/L) Before	SRP[a] (mg/L) After	Absolute Change (mg/L)	Relative Change (%)[b]	Significance[c] ANCOVA	Significance[c] WRS
NF020	High	0.80	0.65	−0.15	−18.6	ns	*
GB040	High	1.13	0.87	−0.26	−23.4	*	*
GB025	High	1.20	0.97	−0.23	−19.3	ns	*
IC020	Moderate	0.54	0.61	+0.07	+12.3	ns	ns
SC020[d]	None	0.14	0.13	−0.01	−3.7	na	ns
SF020	None	0.030	0.029	−0.001	−3.3	ns	ns
SP020	None	0.021	0.015	−0.006	−28.6	*	*

[a] Back transformed from natural log into original linear scale as SRP(Before) = e^{before} and SRP(After) = e^{after}, where "before" and "after" represent corresponding flow-adjusted means (on natural log scale) from ANCOVA, and *e* is the base of the natural logarithm (approx. 2.7183).

[b] Percent change on the linear scale was calculated as: {[SRP(After) − SRP(Before)] / SRP(Before)} × 100.

[c] Significant differences between the "before" and "after" concentrations are for ANCOVA and Wilcoxon rank sum tests, respectively: ns = non-significant, * = significant at α = 0.10, and na = not applicable.

[d] Percent change for SC020 is presented for flow-unadjusted median values rather than for flow-adjusted values because the flow-concentration relationship changed over the analysis period.

At GB025, significant differences in SRP were not indicated between the two periods based on ANCOVA, although a slight downward trend was indicated from the WRS test (table 4). The flow-SRP relationship at site GB025 stayed fairly consistent during the "before" and "after" periods, although the "after" regression line had a lower intercept than the "before" regression line, indicating the potential for minor, albeit not statistically significant, changes in SRP concentrations (fig. 5a). The flow-SRP concentration relationship for GB040 (fig. 5b) showed that the reduction in SRP concentration during the manure composting program was greater under higher flow conditions. SRP concentrations at site NF020 decreased at lower flow conditions but were similar at higher flow (fig. 5c). These regressions may partly explain why the statistical significance for a reduction in SRP concentration at NF020 was apparent only with the WRS test and not the ANCOVA (table 4).

With regard to total P, there was no significant difference in EMCs during the two time periods at sites NF020, GB025, SF020, and SC020 (table 4), but a significant decrease was indicated from the WRS test at GB040. Significant increases

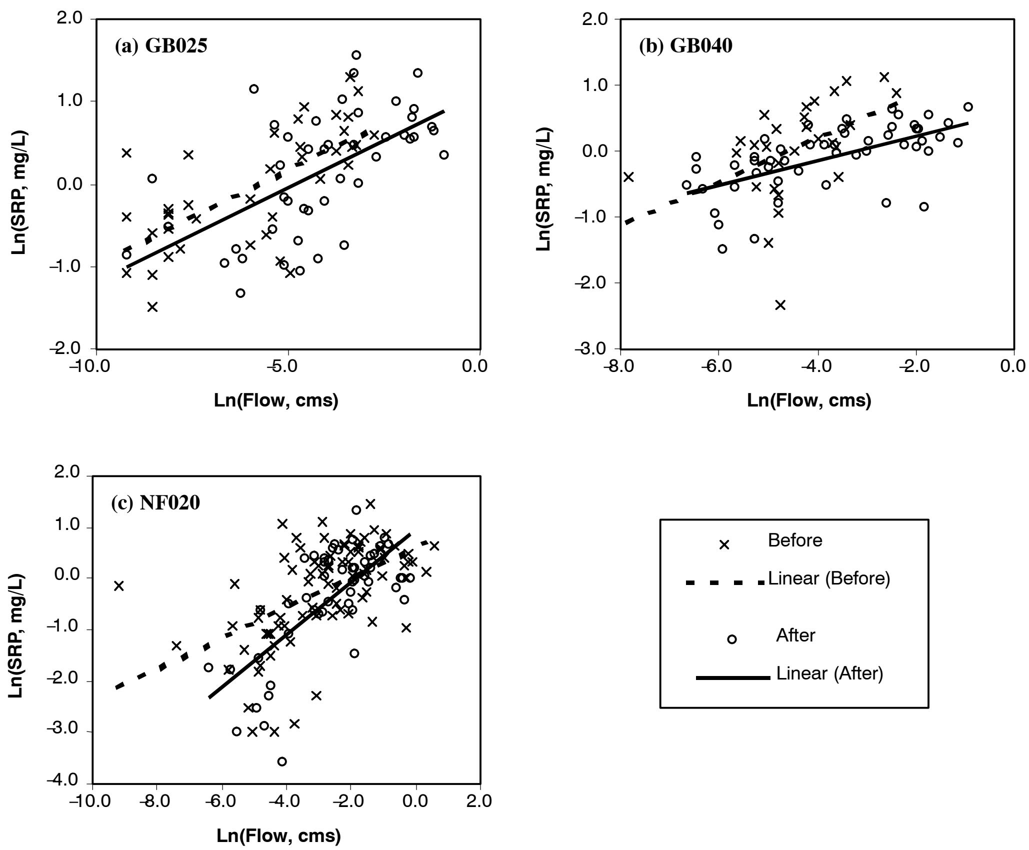

Figure 5. Relationship of event mean concentrations of SRP to average storm flow for sites (a) GB025, (b) GB040, and (c) NF020. Ln represents the natural log of the data. Regressions shown are statistically significant (α = 0.10).

in EMCs of total P and TSS concentrations were indicated at sites IC020 and SC020. At sites NF020, GB025, and GB040, which had a high dairy impact and high expected impact from the manure composting program, the ratio of SRP to total P on average decreased from 0.40 “before” to 0.34 “after” the initiation of the program due to significant decrease in SRP (table 4). At site IC020, a similar decrease in the SRP to total P ratio was observed from about 0.58 “before” to 0.48 “after” the initiation of the program. In this case, the decrease in the SRP to total P ratio was due to an increase in particulate P associated with TSS. Generally, SRP makes up a larger proportion of the total P in runoff from non-cultivated lands, such as pastures and fields with reduced tillage, whereas particulate P is the major portion of the P transported in runoff from cultivated land (Sharpley, 1995; Jarvie et al., 1998). It is speculated, but cannot be proven from the data available, that changes in land use, such as an increase in cropland farming, may be responsible for the increased concentrations in TP and TSS indicated at sites SC020 and IC020.

While decreases in P constituents were expected with the manure composting program, the expectation for changes in N constituents were less certain. Although less manure was applied to the land during the manure composting program, it is likely that producers applied more commercial N to meet crop needs. Data from Riesel, Texas, show that as less poultry litter is applied, more commercial N is applied, which results in more N readily available for runoff losses (Harmel et al., 2004). The water quality results for NH_3-N were mixed (table 4). Ammonia decreased at sites GB040 and SP020 and increased at site IC020. At site IC020, increases in EMCs of NO_2-N+NO_3-N and TKN were apparent during the period after the implementation of the manure composting program. Similarly, site SF020 showed an increase in NO_2-N+NO_3-N, TKN, and TSS.

The increases in NO_2-N+NO_3-N, TKN, and TSS at sites IC020, SF020, and SP020 appeared to be directly related to changes in the flow-concentration relationship between the “before” and “after” periods (graphs not shown). At the same flow level, higher concentrations occurred in storm events during the period “after” than “before” the initiation of the manure composting program. The reason for these differences in the concentration-flow relationships may have little to do with the haul-off of manure, because both sites SF020 and SP020 contain very limited or no impact from dairy operations based on land use (table 1). The watershed area above site IC020 is also only moderately impacted by dairy waste application (table 1). It is uncertain what other factors may be causing these increases, although it is speculated that changes in land use, such as an increase in cropland farming, would increase concentrations of TSS and related constituents.

The observation of a significant decrease in SRP concentration at GB040 and a general decreasing SRP concentration (although not statistically significant) at other sites involved in the manure composting program gives initial indications that the program is working. Removing dairy manure that would have been land applied reduces P inputs to the land. Reduction in P inputs to the land, in turn, is considered among the direct methods used to reduce P concentration from water bodies (Bottcher et al., 1995). However, in large-scale studies such as this, reductions in P inputs may not directly translate into improvements in water quality since there is no control on systematic variations in source factors and transport processes of P in the watershed (Gburek et al., 2000). Based on a review of the literature on best management practice (BMP) effectiveness for P pollution control, Gitau et al. (2005) identify slopes, soils, location, and study scale to be factors that influence BMP effectiveness through their control on P source and landscape P transport processes. According to Eckholm et al. (2000), the effect of scale appears to be a more important control factor for SRP than total P, TSS, or N. They reported increased losses of SRP per unit area with increased watershed area. The losses of total P, TSS, and N per unit area did not depend on watershed size (Eckholm et al., 2000).

The lack of more significant improvements in water quality, especially SRP concentration, following manure removal from microwatersheds with a long-term history of manure application was anticipated for two reasons. First, although direct P inputs to the land were decreased with implementation of the manure composting program, instream improvements generally lag improvements on the land (Clausen et al., 1992; Meals, 1992, 1996; Nikolaidis et al., 1998). Based on field monitoring data and mathematical modeling, Nikolaidis et al. (1998) reported less than 1.5% reduction in N export after three years following a 100% reduction in fertilizer and manure input to agricultural land in north-central Connecticut. They attributed the lack of immediate response in water quality to the non-linear response of watersheds to implementation of land management practices. Nikolaidis et al. (1998) offer two reasons for non-linearity in watershed response: (1) inherent watershed characteristics and hydrochemical processes that delay nutrient loading in response to rainfall runoff, and (2) land use patterns and position of contributing sources within a watershed. Phosphorus fits this non-linear response in that residual SRP can be released from the land and from the resuspension of sediments at elevated flows within the stream system (Brannan et al., 2000). Therefore, the positive effect of manure removal on water quality will be achieved only if sufficient time is given for the nutrient and the hydrological systems to respond, such that P sinks are no longer sources of P to water bodies (Spooner et al., 1985; Sharpley and Rekolainen, 1997).

The second reason more significant improvements in water quality were not expected is because only a relatively short time period of post-treatment monitoring data were available for analysis (about four years). When only short-term post-treatment monitoring data are available, it is often difficult to observe significant improvements in water quality, because the small change that may occur can easily be masked by the high variability in the data. Hydrologic and long-term weather variation account for a large part of the variability in water quality data, thus confounding the evaluation of changes in water quality with changes in management practices (Soranno et al., 1996; Bishop et al., 2005). The “before” and “after” monitoring design is based on the assumption that natural events (e.g., weather conditions) have, on average, remained the same during the two monitoring phases (Smith, 2002). However, historical precipitation data for Stephenville, Texas, show that precipitation after the start of the manure composting program in November 2000 was below average except in 2002 and 2004 (fig. 6). Before the start of the manure composting program, most years showed precipitation well above the long-term average. While rarely does a year represent “average” or

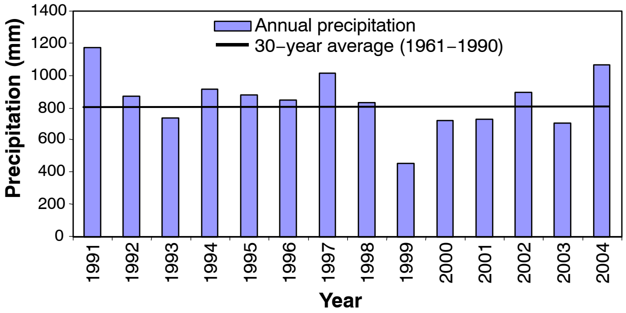

Figure 6. Temporal variability of annual precipitation at Stephenville, Texas. Data obtained from the National Weather Service.

normal precipitation conditions, it is expected with more monitoring that conditions "after" the implementation of the manure composting program will start to more closely resemble the conditions "before" the program began.

It has been suggested that loading concentration variability is more closely correlated with hydrologic variation than with changes in land treatment (Moog and Whiting, 2002). Given that all variables other than land treatment are constant, a paired watershed approach (Spooner et al., 1985; Meals and Hopkins, 2002; Smith, 2002) and incorporation of multiple covariates (flow, precipitation, rainfall intensity, temperature, antecedent moisture conditions, etc.) in data analysis (McDowell and Sharpley, 2002; Bishop et al., 2005) might alleviate this lack of control over hydrologic and climatic variation. A paired watershed approach, however, could not be used because the treatments were employed (manure composting program) on a voluntary basis. Consequently, the microwatersheds considered did not satisfy the requirements of a paired watershed monitoring design. Continued monitoring, however, should allow a more representative data set, ameliorating the impact of climatic and hydrologic variation present in the four years currently available for evaluation.

Conclusions

Despite only four years of post-implementation monitoring, the manure composting program appears to be having an impact on water quality in the North Bosque River. Statistically significant reductions (19% to 23%) in SRP concentrations were observed at sites with the highest levels of participation in the manure composting program. Currently, the manure composting program is funded through August 2006. With the implementation of the North Bosque River TMDL and with the national need for managing animal byproducts, a variety of other programs are also targeting nutrient runoff from application fields. Examples include the requirement of nutrient management plans for concentrated animal feeding operations (CAFO; Federal Register, 2002) and EQIP incentives through NRCS for nutrient management and manure transfer (NRCS, 2004). The USEPA CAFO rule, passed in February 2003, and Texas CAFO rules under TCEQ both require development and implementation of nutrient management plans that consider N and P (TCEQ, 2004). Responsibilities stemming from the North Bosque River TMDL for SRP require that the TSSWCB take nutrient management planning a step further by aiding in the development of comprehensive nutrient management plans (CNMPs) and water quality management plans (WQMPs), respectively, for permitted and unpermitted animal feeding operations in the watershed (TCEQ and TSSWCB, 2002). A CNMP targets not only animal waste application fields but the entire production system to ensure that both agricultural production goals and natural resource concerns dealing with nutrient and organic byproducts are addressed.

While the nutrient management activities under the CAFO rule and EQIP programs do not necessarily lead to the removal of manure from the watershed, they should better direct utilization of manure on the land, leading to decreased nutrient runoff. A complicating factor, which will be difficult to assess, is the cumulative impact of manure application as more land in the watershed is used for dairy waste application. With these multiple programs in the watershed, it will also become more difficult to isolate the impact of the manure composting program in future data analyses, but possible if more detailed information can be obtained on land management practices within the different watersheds along with continued water quality monitoring.

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