ANIMAL WASTE BMP IMPACTS ON SEDIMENT AND NUTRIENT LOSSES IN RUNOFF FROM THE OWL RUN WATERSHED

K. M. Brannan, S. Mostaghimi, P. W. McClellan, S. Inamdar

ABSTRACT. *The results of the 10-year study conducted in the Owl Run watershed clearly indicate the beneficial impacts of the best management practices (BMPs) on the surface water quality. The main objective of the study was to determine the effectiveness of a system of animal waste BMPs for improving surface water quality. Precipitation, streamflow, total suspended solids, nitrogen (N), and phosphorus (P) water quality parameters were measured at the main outlet and in three subwatersheds. A pre- and post-BMP comparisons of annual water quality parameters were performed. Reductions in all forms of N and most forms of P were observed due to the implementation of BMPs. For the average annual values at the main watershed outlet, BMPs were effective in reducing both loads and concentrations of all forms of N with the largest reductions in soluble organic N (62%) and the smallest reduction for nitrate-N (35%). Furthermore, BMPs were effective in reducing both loads and concentrations of most forms of P with the largest reductions in particulate-P (78%) and the smallest reduction for soluble P (39%). However, BMPs were not effective in reducing orthophosphorus-P. The system of BMPs implemented in the Owl Run watershed was effective in reducing nutrient loadings, especially N loadings. However, when P is the main water quality concern, implementation of P-based nutrient management plans should be considered.*

Keywords. *Nonpoint source pollution, Animal waste, Nutrient management, Water quality monitoring.*

Nonpoint source pollution is transported primarily by runoff from urban, agricultural, mining areas, and construction sites. Agricultural activities are being increasingly blamed for deterioration of surface and ground water resources in the United States. Significant progress has been made in developing technologies for controlling point sources, while until recently nonpoint sources of pollution had been relatively neglected. Runoff carries sediment, organic matter, bacteria, pesticides, metals, nutrients, and other chemicals. Nutrients, primarily nitrogen (N) and phosphorus (P), can be a major problem because they can cause eutrophic algae growth which may reduce oxygen availability and increase turbidity in water bodies. Livestock systems, which utilize pastureland for grazing animals and cropland for disposal of manure waste, are one segment of agricultural production for which the extent of nonpoint source pollution is neither clearly defined nor the effectiveness of best management practices (BMPs) adequately demonstrated.

In 1983, a study by the U.S. Environmental Protection Agency on the decline in water quality of the Chesapeake Bay indicated that point and nonpoint sources of pollution were among the main causes of the Bay's decline (USEPA, 1983). In particular, the study indicated that nonpoint sources contributed about 67% of the N and 39% of the P entering the Bay. Furthermore, agriculture was estimated to be responsible for 60 and 27% of the N and P loadings from nonpoint sources, respectively. Consequently, in December 1987, the Governors of Pennsylvania, Maryland, and Virginia, the mayor of the District of Columbia, and the Administrator of the EPA pledged to address nonpoint sources as well as other sources of pollution to restore and protect the Chesapeake Bay. This commitment, known as the Chesapeake Bay Agreement of 1987, requires the signatory States to implement cost-sharing programs targeted at reducing nonpoint source pollution of the Bay and its tributaries.

Virginia's agricultural cost-sharing program was initiated in response to the Chesapeake Bay program and was designed to encourage voluntary implementation of BMPs such as conservation tillage and installation of animal waste facilities by farmers. Animal waste management involves both storage and proper utilization of waste as fertilizer on agricultural land in order to improve crop production and reduce transport of pollutants by runoff. Timing, method, and rate of application are controllable management factors that influence both the effectiveness of the animal waste as a fertilizer and the degree to which runoff pollution is prevented (Sharpley et al., 1994).

While there is documented evidence on the water quality advantages of BMPs on field-size plots, the effectiveness of BMPs, especially animal waste management practices, on large watersheds with varying topography, land use, soils, and geology is relatively unknown. Thus, a comprehensive nonpoint source monitoring program was undertaken in 1986 to quantify

Article was submitted for publication in November 1999; reviewed and approved for publication by the Soil & Water Division of ASAE in July 2000.

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the effects of animal waste BMPs on improving runoff water quality from the Owl Run watershed located in Fauquier County, Virginia. The objective of the study was to evaluate long-term effectiveness of animal waste BMPs in reducing sediment and nutrient losses in surface runoff.

METHODS

A pre- versus post-BMP design (Spooner et al., 1985) was used for the Owl Run watershed project. The total duration of the monitoring project was 10 years. The pre-BMP period started at the initialization of monitoring in July 1986 and continued until July 1989. This resulted in approximately three years of data for the pre-BMP period. The post-BMP period began in July 1989 and continued until the end of the monitoring project (June 1996), resulting in seven years of data. In this article, the annual average values for various parameters monitored are reported. No statistical analysis is performed on the annual average data because of the limited number of observations (years), especially in the pre-BMP period. The information in this article is intended to provide reductions in sediment and nutrients due to implementation of BMPs, which could be used when developing pollution control strategies for watersheds similar to the Owl Run watershed.

WATERSHED DESCRIPTION

The Owl Run watershed, which is 1,153 ha in size, is located in Fauquier County, Virginia. This watershed was selected for monitoring because of its high concentration of dairy farms and lack of animal waste management practices at the time of its selection. Erosion from the agricultural land was mainly attributed to the fact that a large area of cropland must be left without protective vegetative cover over the winter to provide land for manure spreading (Mostaghimi et al., 1989).

The climate of the Owl Run watershed is of the humid continental type with hot humid summers and mild winters. The average annual rainfall for Owl Run watershed is 1000 mm. Precipitation is fairly well distributed throughout the year, although the greatest amount occurs in the spring and summer. Because of the characteristics of the summer rains, runoff is usually greatest during summer period (Mostaghimi et al., 1989).

The topography of the Owl Run watershed is consistent with both the Blue Ridge Mountains and Piedmont physiographic provinces. The Piedmont Plateau comprises 80% of Fauquier County and is sub-divided into rolling to steep Piedmont Plateau, undulating to rolling Triassic Plane of the Piedmont Plateau, and undulating to rolling Piedmont Plateau. The Blue Ridge Mountain Province in the northwest part of the county has terrain that is mainly steep and rugged.

Soils within the watershed are mostly shallow (0.3 to 0.6 m) silt loams, overlying Triassic shale. Approximately 72% of the soil series within the watershed are comprised of the Penn (40%, *Ultic Hapludalfs*), Bucks (16%, *Ultic Hapludalfs*) and Montalto (16%, *Ultic Hapludalfs*) associations (SCS, 1956). The Penn series is derived from Triassic Red shale and sandstone, specifically, the silt loam is from the shale and the loam is from the sandstone. These soils are shallow and excessively drained, occurring mainly in undulating to rolling relief. The Penn series typically has medium runoff and medium to rapid internal drainage. Soil permeability is moderate while the water holding capacity is poor. The Bucks series, developed over Triassic red shale and sandstone, is moderately deep, well-drained upland soils. This series typically occupies moderately large areas on broad, undulating ridges that join the Penn series. The Bucks series has slow to medium runoff with medium internal drainage. The Montalto series, developed over fine grained Triassic diabase, is moderately shallow and well-drained. These soils have a medium runoff potential and internal drainage (SCS, 1956).

Nearly 70% of the Owl Run watershed is in agricultural production, including both cropping and livestock activities. The remainder of the watershed includes residential, commercial, transportation, and forested areas. Corn production occupies approximately 26% of the watershed area, employing both conventional and no-tillage practices. Roughly half of the corn crop follows a rye cover or small grain rotation. The majority of hay fields remain as grass for three to four years followed by one year of corn planting. Typically, the corn crop is followed by hay, seeded with a small grain companion crop (Mostaghimi et al., 1989). A summary of the land use within the Owl Run watershed during the monitoring period is listed in table 1. Five major dairy and several beef operations were functional within the Owl Run watershed during the monitoring project. Livestock numbers increased by 2% from 1,144 (1,000 Dairy and 144 other) in the pre-BMP period to 1,164 (1,050 Dairy and 114 other) the post-BMP period (Mostaghimi et al., 1989). This increase occurred only in the dairy operations, as the beef operations experienced a decline in numbers over the course of the investigation.

Prior to the construction of the animal waste storage facilities, farmers land-applied livestock waste materials on a daily or weekly basis, regardless of the ground temperature. Researchers (Crane et al., 1983; Eghball and Power, 1994) have reported on the risks associated with this application schedule and suggest that storing waste material is an efficient means by which to reduce the potential for nonpoint source pollution. During the pre-BMP period, the selection of fields to receive waste

Table 1. Summary of land use in Owl Run watershed

Year	Farm-stead (ha)	Crop-land (ha)	Non-Ag* (ha)	Forest (ha)	Pasture (ha)	Inactive Ag Land† (ha)	Other‡ (ha)
1986	25.2	336.2	117.0	307.7	215.8	71.4	89.7
1987	25.2	325.4	117.0	306.7	199.4	71.4	117.8
1988	25.2	397.8	117.1	306.7	211.6	13.8	90.7
1989	25.2	343.7	117.1	304.3	218.0	29.9	124.6
1990	25.2	394.1	117.1	304.3	228.8	35.0	58.4
1991	20.0	381.9	111.6	309.3	263.2	68.0	9.1
1992	20.0	368.0	111.6	309.2	264.4	80.8	9.1
1993	20.0	429.4	110.6	304.9	275.8	13.9	8.2
1994	20.0	410.3	114.2	305.2	291.0	14.2	8.0
1995	20.0	410.3	114.2	305.2	289.9	15.5	8.0
1996	20.0	410.3	114.1	305.2	289.9	15.5	8.0
Pre-BMP average	25.2	356.4	117.1	306.5	209.3	44.6	103.9
Post-BMP average	21.1	395.0	113.6	306.1	266.7	36.0	24.5

* Non-ag land includes residential areas other than farmsteads and roads.
† Inactive ag land includes retired cropland and pasture areas.
‡ Other includes ponds, 'no report', and grassed waterways.

applications prior to the implementation of the waste storage facilities was based primarily on the proximity to manure sources. The construction of waste storage facilities within the Owl Run watershed impacted the selection of the fields receiving manure applications in that land operators had the flexibility of applying animal waste to fields where it could be best utilized, rather than those fields most readily accessed. Personnel from the Virginia Division of Soil and Water Conservation developed nutrient management plans for each of the dairy operations. Technical support for the land-operators concerning these management methods was available through the local USDA, NRCS office. Stream fencing was also constructed as a BMP in the Owl Run at selected areas where animals had direct access to streams. Some of the main BMPs implemented include manure storage structures, nutrient management (based on nitrogen crop needs), stream fencing, watering troughs, and stream crossings for animals. Other BMPs implemented to a lesser extent included winter cover crops, field strip cropping, and grassed waterways. A complete listing of BMPs is provided in Mostaghimi et al. (1999) and is not listed here in the interest of brevity. The BMPs were implemented on a farm basis. This made it difficult to associate BMPs with a particular subwatershed. In any case, measuring the effectiveness of specific BMPs was not the objective of this study. Rather, measuring the effectiveness of a system of BMPs was the objective of this study and the resolution that BMP implementation was tracked (farm basis) was considered sufficient.

Monitoring System and Data Collection

A pre versus post-BMP implementation data collection and analysis design was used for the Owl Run Project (Spooner et al., 1985). The pre-BMP monitoring of the Owl Run watershed began in the spring of 1986. Approximately three years later, BMP implementation began and monitoring continued through June 1996. Thus, the 10 years of monitoring includes both the pre- and post-BMP data collection periods. Specific elements of the monitoring system included: wet and dry weather physical and chemical monitoring of surface and groundwater, biological monitoring of surface water, physical and chemical analysis of soils, and chemical analysis of atmospheric deposition (Mostaghimi et al., 1989). The focus of the chemical component of surface runoff was nutrients, including both soluble and particulate forms, organic chemicals, insecticides, and herbicides. A comprehensive QA/QC plan was developed and followed throughout the project (Mostaghimi, 1989).

Four surface runoff monitoring sites were established within the Owl Run watershed (fig. 1). Six pre-existing private wells were employed to monitor groundwater quality. However, after 12 months of data collection, the groundwater monitoring was discontinued, as no water quality impairments were detected. Station A was at the outlet of the watershed and the data collected at this site was intended to illustrate the overall response of the entire 1153 ha watershed to the implementation of the BMPs. The runoff collected at station B (45 ha) was installed as a means by which to exclude the urban runoff from the town of Calverton, Virginia. Since mainly agricultural runoff was collected at station C, this station was installed to demonstrate the efficiency of cropland BMPs in reducing nonpoint source pollution throughout the 462 ha subwatershed. The fourth station, D, drained 331 ha of land including runoff from two of the five dairy operations within the watershed. This monitoring station was intended

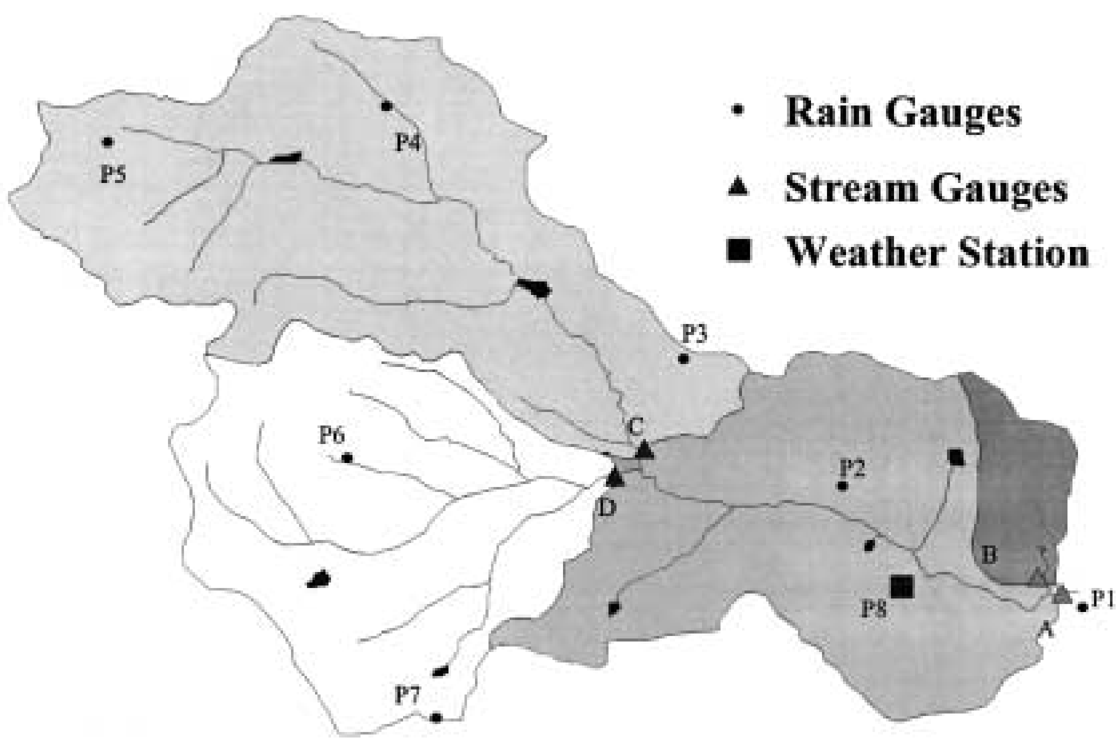

Figure 1–Location of rain gauges, weather, and monitoring stations.

to evaluate the effectiveness of intensive animal waste BMP implementations on stream water quality. The streams in the Owl Run watershed have no baseflow during dry weather, thus any runoff received is primarily due to storm events.

Streamflow and meteorological instrumentation installed in the watershed included: four automatic water samplers, eight recording rain gauges, meteorological instruments to record pan evaporation, ambient temperature, humidity, solar radiation, wind speed and wind direction, and a precipitation water sampler. A 5:1 Virginia broadcrested V-notch weir was used to measure streamflow at station A for low-flow control while 3:1 Virginia broadcrested V-notch weirs were used at stations C and D. At these three stations, rectangular broad-crested weirs were used over the flood plains to accommodate very high flows. At station B, runoff was measured using a calibrated pipe culvert. Water level at the stations was measured using an FW-1 Belford (Friez FW1) recorder equipped with timer gears and modified with a potentiometer. Discrete stream water samples were collected based on changes in the stream stage using automatic samplers that were installed at all stations. The automatic samplers were controlled by microloggers (Mostaghimi et al., 1989). The specific monitoring data used in the study reported herein are precipitation, streamflow volume, total suspended solids (TSS), ammonium-N, total Kjeldahl N, filtered total Kjeldahl N, nitrate-N, total P, filtered total P, and orthophosphorus-P.

Data Sets

For all of the data categories, data sets were generated at a monthly time-step. Hourly data were accumulated to generate the monthly data. A separate sub-set of monthly data set was created for the pre- and post-BMP periods. The cutoff date used to separate the Pre- and Post-BMP periods was 1 July 1989. Over 6,800 water quality samples were used to calculate the mass loads. These samples included both grab samples and samples collected using the automatic samplers during storm events. The mass loads were calculated using hourly flow volume observations. The sample concentrations along with the hourly streamflow volume observations were used to derive the mass load data. A previously developed computer program was used to estimate the pollutant loads (Mostaghimi et al., 1989). The flow-weighted concentrations were generated by dividing the monthly mass loads by the corresponding monthly accumulated streamflow. The average annual loads for each period were calculated by accumulating the monthly values for each period and dividing these sums by the ratio of the number of months in the period divided by 12. The same procedures were used to calculate the average annual streamflow for the pre-BMP and post-BMP periods. The average annual flow-weighted concentrations were estimated as the ratio of the average annual load and the average annual streamflow. The contributions from subwatershed B were removed for the loads and flow-weighted concentrations reported at station A since no BMPs were implemented in the B subwatershed during the study period.

Results and Discussions

Precipitation and Runoff

The average annual precipitation amounts for the Owl Run watershed during the pre- and the post-BMP periods were 1054 and 1075 mm, respectively (table 2), indicating a slight increase (2%) in precipitation for the post-BMP period. Since rainfall values were Theissen-weighted, based on eight stations distributed across the Owl Run watershed, the total values presented here are applicable for all three watersheds (A, C, and D). The long-term annual average rainfall for the Owl Run watershed is 1000 mm (Mostaghimi et al., 1989), which meant that precipitation during both the pre- and post-BMP periods were slightly above the long-term average.

Average annual streamflow depths (streamflow volume divided by watershed area) for station A during the pre and post-BMP periods were 345 mm and 440 mm, respectively (table 2). Compared to the 2% increase in rainfall depth, the increase in streamflow at station A during the post-BMP period was considerably higher (28%). The average annual flows from the main watershed were similar to the average values reported for the Piedmont region. Darling (1962) reported an average annual discharge of 410 mm yr^{-1} for the Piedmont region. The discharge observed at station A was similar to the regional average (the pre-BMP 345 mm and post-BMP 440 mm). The increase in

Table 2. Average annual hydrologic and nutrient loads at stations A, C, and D

Watershed	A			C			D		
Parameter	Pre-BMP	Post-BMP	% Change*	Pre-BMP	Post-BMP	% Change*	Pre-BMP	Post-BMP	% Change*
Precipitation (mm)	1,054	1,075	2	---†	---†	---†	---†	---†	---†
Streamflow (mm)	345	440	28	114	155	36	87	98	13
TSS (kg/ha)	1,073.00	872.80	–19	325.20	492.00	51	2,024.80	1,671.70	–17
Ammonium-N (kg/ha)	3.22	1.77	–45	0.88	0.41	–53	1.46	1.11	–24
Nitrate-N (kg/ha)	9.70	8.09	–17	4.48	2.95	–34	9.58	9.19	–4
Total N (kg/ha)	30.50	19.83	–35	18.61	7.10	–62	28.88	22.03	–24
Soluble N (kg/ha)	19.70	13.14	–33	8.94	4.84	–46	16.53	13.11	–21
Soluble organic N (kg/ha)	6.79	3.28	–52	3.58	1.48	–59	5.49	2.80	–49
Particulate N (kg/ha)	10.81	6.70	–38	9.67	2.26	–77	12.35	8.92	–28
Total P (kg/ha)	9.33	4.30	–54	2.55	1.63	–36	6.78	5.11	–25
Soluble P (kg/ha)	3.42	2.65	–23	0.46	1.00	117	2.18	2.10	–4
Soluble organic P (kg/ha)	1.98	0.67	–66	0.36	0.64	78	1.15	0.53	–54
Particulate P (kg/ha)	5.91	1.65	–72	2.09	0.63	–70	4.59	3.00	–35
Orthophosphorus P (kg/ha)	1.45	1.98	37	0.10	0.35	250	1.03	1.57	52

* Percent Change = [(Post – Pre)/Pre] × 100.

† Same as A.

streamflow observed in the post-BMP period may be related to an increase in storm intensity also observed during the post-BMP period. The average annual rainfall intensity increased over 37% in the post-BMP period (1.33 mm h^{-1}), as compared to the pre-BMP phase (0.97 mm h^{-1}). The increased storm intensities resulted in a larger amount of runoff generated in a shorter time period during a storm, thus increasing streamflow. Streamflow values observed at stations C and D were less than those recorded at station A. The pre- and post-BMP average annual streamflows measured at station C were 114 mm and 155 mm, respectively (table 2), with a 36% increase in the post-BMP period. At station D, the pre- and post-BMP average annual streamflows were 87 mm and 98 mm, respectively (a 12% increase in the post-BMP period).

Jordan et al. (1997a) measured annual streamflow discharges from a number of Piedmont watersheds of varying sizes and landuses. Based on their observations, Jordan et al. (1997a) found that discharge was generally lower for the smaller watersheds, as was the case for the Owl Run watershed. Watershed A had the largest area (1157 ha) and the largest discharge per area for both periods. Subwatershed C had the next largest area (462 ha) and the second largest discharge per area for both periods. Finally, subwatershed D was the third smallest subwatershed by area (328 ha) and had average annual discharges that were smaller than both A and C.

The average annual water yields for the Owl Run watershed were also comparable to the values reported for similar watersheds. The average annual water yield is the ratio of the average annual discharge depth to the average annual precipitation depth. Jordan et al. (1997a) reported an average water yield of 0.37 for Piedmont watersheds located in the Chesapeake drainage basin. The average water yields for the pre-BMP and post-BMP periods at Owl Run (**A**) were 0.42 and 0.41, respectively, which are very similar to the regional value reported by Jordan et al. (1997a).

BMPs implemented in the Owl Run watershed such as animal waste storage and nutrient management do not affect runoff production processes directly. Therefore, we do not expect any of the differences in runoff observed between the pre-BMP and post-BMP periods to be the result of changes in management practices. Although there were some BMPs implemented that would impact the generation of runoff (such as field strip cropping), the extent of their implementation was small (35 ha of field strip cropping) and considered negligible. The impacts of the BMPs were expected to be most evident in the nutrient water quality parameters.

SEDIMENT

Total suspended solids (TSS) concentrations and mass loads discharged from watersheds A, C, and D were determined from streamflow samples collected at the watershed outlets. Sediment concentrations measured in the Owl Run watershed were representative of the combined influence of field and in-stream sediment transport mechanisms. Several in-stream mechanisms, such as re-suspension and deposition within the stream and sediment generation via streambank erosion, could influence TSS concentration. In-stream sediment dynamics are dictated to a large extent by variations in streamflow. Hence, as opposed to edge-of-the-field measurements that more likely indicate direct influences of BMP implementation, streamflow sampling of TSS may include influences of instream processes that may mask the impacts of BMP implementation. Furthermore, although TSS concentrations can provide an indication of how much sediment is being carried in a stream, they do not include a measure of larger particles that are carried along the streambed as bed load during high flows.

For the Owl Run watershed, the average annual TSS load decreased by 19% during the post-BMP period (table 2). Correspondingly, the flow-weighted concentrations decreased by 36% (table 3). The average annual TSS load observed at C increased by 51% from 325 kg ha^{-1} for the pre-BMP period to 492 kg ha^{-1} for the post-BMP period (table 2). A smaller increase in flow-weighted concentration for TSS of 18% was observed at station C (table 3). Reductions of 17% and 27% were observed in the average annual TSS load and flow-weighted concentration at station D (table 2), respectively.

The reductions in TSS loads and flow-weighed concentrations observed at stations A and D are most likely the result of the BMPs, such as stream fencing. Most of the animals in the Owl Run watershed were located in the D subwatershed. The exclusion of the animals from the

Table 3. Average annual hydrologic parameters and nutrient flow-weighted concentrations at stations A, C, and D

Watershed	A			C			D		
Parameter	Pre-BMP	Post-BMP	% Change*	Pre-BMP	Post-BMP	% Change*	Pre-BMP	Post-BMP	% Change*
Precipitation (mm)	1054	1075	2	---†	---†	---†	---†	---†	---†
Streamflow (mm)	345	440	28	114	155	36	87	98	13
TSS (g L^{-1})	0.31	0.20	–35	0.11	0.13	18	0.66	0.48	–27
Ammonium-N (mg L^{-1})	0.93	0.40	–57	0.31	0.10	–68	0.48	0.32	–33
Nitrate-N (mg L^{-1})	2.81	1.84	–35	1.57	0.76	–52	3.13	2.65	–15
Total N (mg L^{-1})	8.83	4.50	–49	6.52	1.84	–72	9.43	6.35	–33
Soluble N (mg L^{-1})	5.71	2.98	–48	3.13	1.25	–60	5.40	3.77	–30
Soluble organic N (mg L^{-1})	1.96	0.75	–62	2.82	1.15	–59	1.79	0.81	–55
Particulate N (mg L^{-1})	3.13	1.52	–51	3.39	0.55	–84	4.03	2.57	–36
Total P (mg L^{-1})	2.70	0.98	–64	0.89	0.42	–53	2.22	1.47	–34
Soluble P (mg L^{-1})	0.99	0.60	–39	0.16	0.26	63	0.71	0.60	–15
Soluble organic P (mg L^{-1})	0.57	0.15	–74	0.13	0.17	31	0.38	0.15	–61
Particulate P (mg L^{-1})	1.71	0.38	–78	0.73	0.16	–78	1.50	0.86	–43
Orthophosphorus P (mg L^{-1})	0.42	0.45	7	0.03	0.09	200	0.34	0.45	32

* Percent Change = [(Post – Pre)/Pre] × 100.
† Same as A.

streams provided by the fencing protected the stream bank from animal traffic and, in turn, reduced the amount of stream bank erosion. Similar findings were reported by Sheffield et al. (1997) when they investigated the impact of alternative water supplies on the amount of time livestock spent in streams. Sheffield et al. (1997) did not use stream fencing. Instead, alternative water supplies provided for the cattle resulted in a 92% reduction in the time spent by livestock in the streams. Sheffield et al. (1997) also observed large reductions in TSS loads and concentrations (upwards of 40%) when the livestock were not in the streams. One reason the reductions (17% for load and 27% for flow-weighted concentrations) observed in subwatershed D were not as great as those reported by Sheffield et al. (1997) could be related to the size of the study area. The sites studied by Sheffield et al. (1997) ranged from 14.2 to 23.3 ha. Also, Sheffield et al. (1997) collected the samples at the edge of pastures (or paddocks). These small sites would respond much more quickly than the 328 ha D subwatershed.

The increase in the TSS load and flow-weighted concentration from the C subwatershed may indicate the need for more cropland soil and water conservation practices in that subwatershed. The C subwatershed contained fewer acres of pasture and fewer animals than subwatershed D. Subwatershed C was mostly cropland. The increases of 51% in annual loading and 12% in flow-weighted concentration of TSS at station **C** could also be related of the 11% increase in cropland observed during the project and the 37% increase in storm intensity during the post-BMP period. Although field strip cropping was implemented in some areas during the post-BMP period (a total of 35 ha), no specific conservation practices were reported for the cropland because the major focus of the project was animal waste BMPs, rather than cropland practices.

NITROGEN

Reductions in both N loads and flow-weighted concentrations were observed for A, C, and D due to implementation of BMPs. The changes in average annual flow-weighted concentrations observed at station A are presented in figure 2. Reductions were observed in total N and in all the other forms of N investigated. For the main watershed (A), the average annual loads are presented in table 2 and the average annual flow-weighted concentrations are presented in table 3. Even though there was a 28% increase in streamflow for the post-BMP period, as compared to the pre-BMP phase, there was a 35% reduction in average annual total N load leaving the Owl Run watershed. In addition, compared to the pre-BMP period, a 49% reduction in the annual average flow-weighted concentrations for total N during post-BMP period was observed at station A. The larger reductions observed for all the flow-weighted concentrations could be due to the dilution effect provided by the increased streamflow in the post-BMP period. Similar reductions were observed for the other forms of N at station A. BMPs reduced the average annual ammonium N load and concentrations by 45% and 57%, respectively. Likewise, there were reductions observed after BMP implementation in annual average loads (17%) and flow-weighted concentrations (35%) of nitrate N. BMPs also reduced particulate N. The average annual loads of particulate N (total N minus soluble N) decreased by 38% (table 2) and the flow-weighted concentrations of particulate N decreased by 51% (table 3). For the aggregated soluble forms of N, the average annual loads decreased by 33% and the flow-weighted concentrations decreased by 48% after BMP implementation. The average annual loads for soluble organic N (soluble N minus ammonium and nitrate N) decreased by 52% and the flow-weighted concentrations decreased by 62% in the post-BMP period as well. The general trend in N reductions for the entire Owl Run watershed in the post-BMP period could be related to the N losses due to BMPs implemented, particularly manure storage structures. Conversion of organic N to inorganic forms of N occurs while manure is stored. The inorganic forms are prone to conversion to ammonia, which is then volatilized to the atmosphere.

Subwatershed C was monitored to investigate the impact of cropland BMPs on water quality. However, the focus of the project was not on cropland erosion, but rather, on the effectiveness of cropland BMPs related to the use of animal waste as a nutrient source. Therefore, BMPs, such as nutrient management, were implemented and only a small portion of the cropland (35 ha of strip cropping) were treated using BMPs that directly address erosion problems. For subwatershed C, BMPs reduced all forms of N despite the 35% increase in streamflow in the post-BMP period (tables 2 and 3). The changes in average annual flow-weighted concentrations observed at station C are presented in figure 2. Among various N forms leaving subwatershed C, the maximum reduction (77%) observed was for particulate N load and the minimum reduction (34%) after BMP implementation was observed for nitrate N load. The corresponding reductions in the average annual flow-weighted N concentrations were 84% for particulate N and 52% for nitrate N. The general trend in N reductions from subwatershed C in the post-BMP period could be attributed to both the N losses due to the storage of the manure as well as due to nutrient management. Since the majority of subwatershed C is under cropland, manure from other parts of the Owl Run watershed is imported to subwatershed C for spreading. The flexibility provided by the manure storage allows for spreading of manure at times when crops need N. Thus, the amount of N lost to runoff is reduced.

Subwatershed D had a high concentration of animals; thus it was monitored to investigate the impact of intensive animal waste BMPs on water quality. As with the A and C watersheds, there were reductions in all forms of N investigated for subwatershed D even though there was a 12% increase in streamflow during the post-BMP period (tables 2 and 3). The changes in average annual flow-weighted concentrations observed at station D are presented in figure 2. The maximum reduction for the average annual N load was 49% in soluble organic N and the smallest reduction was observed for nitrate N (4%). Correspondingly, BMPs caused the maximum reduction in average annual flow-weighted concentrations for soluble organic N (55%) and the minimum reduction (15%) for nitrate N for the. As with watershed A, the reductions observed due to implementation of BMPs in subwatershed D were attributable to the storage of the animal waste. The greatest reduction was in the organic form of N while the

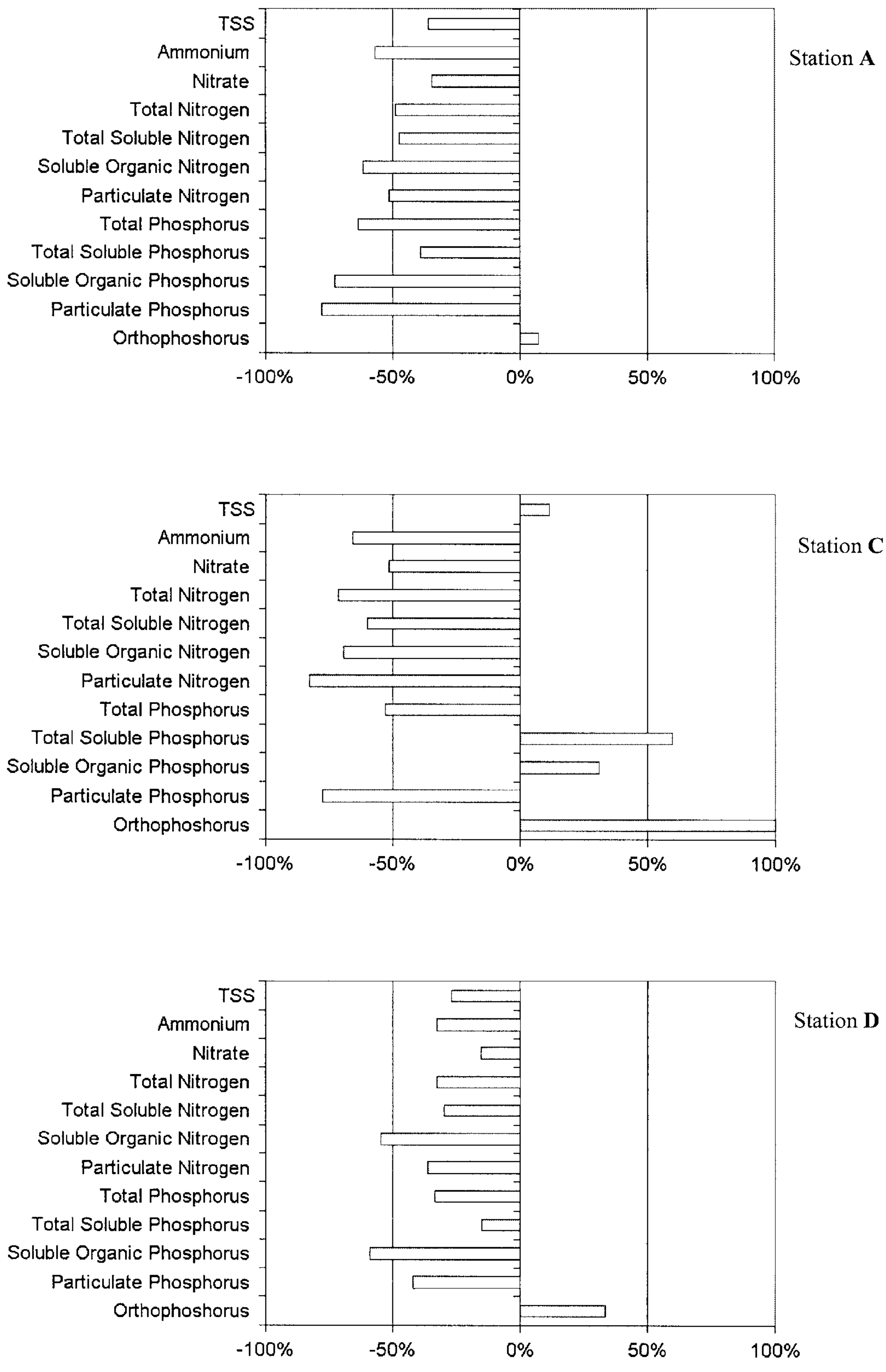

Figure 2–Changes in average annual flow-weighted concentration at stations A, C, and D due to BMPs.

smallest reduction was for the inorganic form of N which are not easily lost to the atmosphere, specifically nitrate N.

The general trend in N reductions for the entire Owl Run watershed may be related to the N losses during the storage of the manure. The two main components of N found in manure are organic N and ammonia N (Collins et al., 1995). The inorganic portion of N in fresh manure is commonly in the form of ammonium N. Storage of manure, especially in slurry form, generally results in the loss of organic N through ammonification and then volitilization of the ammonia N. Organic N is converted to ammonium N, which then volatilizes as ammonia N. Also, storage of manure at high moisture contents may result in the loss of nitrate N by denitrification (Cabrera and Gordillo, 1995). However, the level of nitrate N in manure depends on the presence of nitrifiers, which are microbes commonly found in the soil.

The transformation of organic to inorganic forms of N is evident in the data collected from the Owl Run watershed. In figure 3, the proportions of ammonium, nitrate, soluble organic and particulate N are shown for the pre and post-

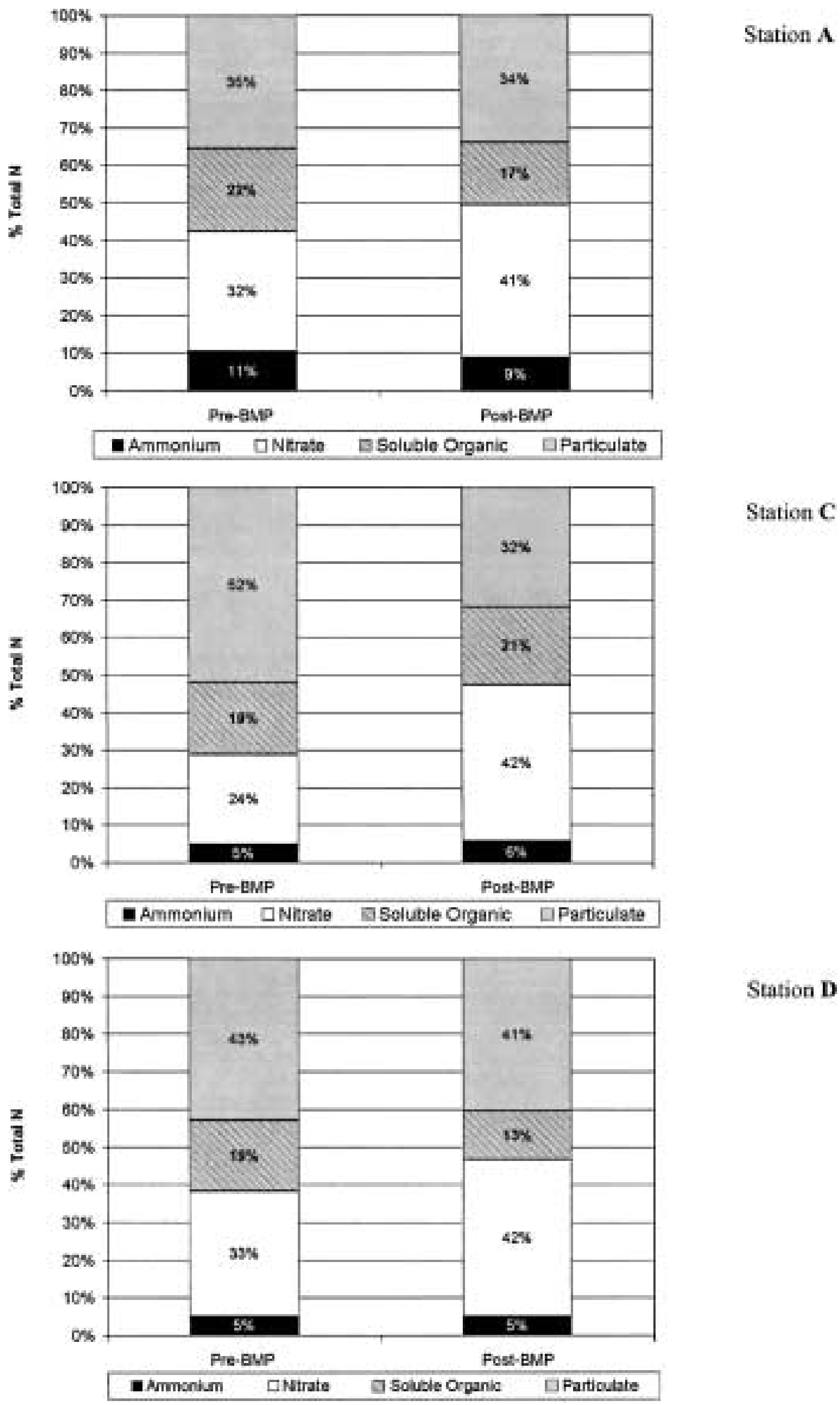

Figure 3–Proportions of total N by species at stations A, C, and D.

BMP periods. In the pre-BMP period, 22% of total N was soluble organic N, compared to only 17% in the post-BMP period. The reduction in soluble organic N resulted in increases in inorganic forms of N. The proportion of N in the soluble inorganic form (nitrate + ammonium) increased from 43% in the pre-BMP period to 50% in the post-BMP period. The transformations of organic to inorganic N are more apparent in the N loadings observed from subwatershed C and D. For subwatershed C, a major increase in the proportion of N in the form of nitrate N occurred from the pre-BMP value of 24% to the post-BMP value of 42% (fig. 3). There was also a large reduction in the portion of particulate N for subwatershed C (52% for pre-BMP period and 32% for post-BMP period) and there was a small increase in the proportion of soluble organic N (19% in the pre-BMP period and 21% in the post). For subwatershed D, the proportion of N in the form of soluble organic N decreased from 19% in the pre-BMP period to 13% in the post phase (fig. 3). This reduction resulted in an increase in inorganic forms of N with the proportion of N in the soluble inorganic form increasing from 38% in the pre-BMP period to 47% in the post-BMP period.

There are both benefits and drawbacks due to the transformation of N from organic to inorganic forms. The main benefit is that the inorganic forms of N are available to plants, thus nutrient value of the manure may increase. The drawback is that these same inorganic forms of N also promote the growth of aquatic plants and algae, thus increases in the proportions of inorganic N may increase the potential for degradation of the aquatic habitat in the receiving waters. Therefore, great care needs to be taken when applying the manure from the storage structures, and application levels should be based on crop needs to reduce the potential for surface or groundwater pollution.

PHOSPHORUS

As with N, there were reductions observed at stations A, C and D for both P loads and flow-weighted concentrations in the post-BMP period, but there was some increases observed in soluble forms of P for all three watersheds. The changes in average annual flow-weighted concentrations observed at station A are presented in figure 2. BMPs reduced the loadings and concentrations of all forms of P, except for orthophosphorus P. The average annual loads and the average annual flow-weighted concentrations observed at station A are presented in table 2 and table 3, respectively. Despite the 28% increase in streamflow, the BMPs reduced average annual total P load and concentrations leaving the Owl Run watershed by 54% and 64%, respectively. As with the N flow-weighted concentrations, the larger reductions observed for all the P flow-weighted concentrations are potentially attributable to dilution effects caused by the increased streamflow in the post-BMP period. Similar reductions in the post-BMP loads were observed for soluble P load (23%), soluble organic P load (66%), and particulate P (72%) at station A. The same was true for the flow-weighted concentrations in the post-BMP period (table 3). The average annual soluble P flow-weighted concentration decreased by 39% in the post-BMP period. Likewise, BMPs reduced annual average flow-weighted soluble organic P concentration (74%) and particulate P (78%).

The only increase observed, after BMPs were implemented, was for orthophosphorus P. The average annual orthophosphorus P load and concentrations increased by 37% (table 2) and by 7% (table 3), respectively. The reduction in organic forms of P in the post-BMP period is related to the conversion of organic P to inorganic forms of P while the manure is stored. Since inorganic forms of P are not lost to the atmosphere, the management flexibility provided by the manure storage structures probably contributes more to the total, soluble, and particulate P reductions. For P, this flexibility mainly impacts the timing of manure applications rather than its location. Since the nutrient management plans were based on crop N needs, some fields are likely to receive excessive levels of P. This over-application is likely the cause of elevated orthophosphorus P loads (table 2) and concentrations (table 3) observed after the implementation of BMPs. However, spreading of manure did not occur daily when storage was available, but rather allowed for application of manure at times when it is less likely to be removed by runoff.

For subwatershed C, increases in some P forms and reductions in others were observed after BMPs were implemented. Reductions occurred in total and particulate P in the post-BMP period (tables 2 and 3). The changes in average annual flow-weighted concentrations observed at station C are presented figure 2. The average annual total P load and concentrations decreased by 36% and 53%, respectively. Compared to the reductions observed for the main watershed (A), larger reductions where observed in the particulate P after BMP implementation for subwatershed C. The average annual particulate P load and concentration decreased by 70% and by 78%, respectively, in the post-BMP period. However, increases were observed in both loads and concentrations for all the soluble forms of P (see tables 2 and 3) after BMPs were implemented. The increases in the soluble forms of P in subwatershed C are most likely the result of the N-based nutrient management plans. The land use in subwatershed C is mostly cropland and manure from other parts of the Owl Run is applied to this watershed. The flexibility provided by the manure storage allows for spreading of manure at appropriate times, when it is less likely to be transported to streams during runoff events. Thus, the amount of particulate P lost to runoff was reduced. The reduction observed for particulate P is mainly the reason for the reduction observed in total P. Conversely, when the amount of manure applied to cropland is based on crop N needs, over-application of P will occur because the N to P ratios of manure are generally less than the N to P ratio needed by crops (Sharpley et al., 1994).

As with watershed A, BMPs reduced all forms of P, except orthophosphorus P from subwatershed D (table 2 and table 3). The changes in average annual flow-weighted concentrations observed at station D are presented in figure 2. The maximum reduction for the average annual P load was 54% for soluble organic P and the smallest reduction after BMP implementation was for soluble P (4%). Similar reductions occurred in the average annual flow-weighted P concentrations leaving subwatershed D. The largest reduction (61%) was observed in soluble organic P concentration and the smallest (15%) was in soluble P. As with watershed A, the reductions observed after BMP implementation in the D subwatershed could be related primarily to the storage of the animal waste. The greatest reductions were in the organic form of P while the smallest reduction was observed for the inorganic form of P. Furthermore, the increase in orthophosphorus P (tables 2 and 3) after BMP implementation was also the result of conversion of organic P to inorganic forms.

The reductions observed in most forms of P, except for the soluble forms, in the Owl Run watershed are related to the transformations of P due to the storage of the manure and the N-based nutrient management of manure applications to cropland (Sharpley et al., 1994). Unlike N, there has not been much research in the past that focused on P transformations in manure storage facilities, but as with N, organic forms of P are converted to inorganic forms by microbial actions during storage. Unlike N, the inorganic P is not lost to the atmosphere and remains in the stored manure until its application. The transformation of organic P to inorganic forms is evident from the increases in the proportions of total P in inorganic forms after BMP implementation. In figure 4, the proportions of soluble organic P, particulate P and orthophosphorus P at station A are shown for the pre and post-BMP periods. In the pre-BMP period, only 21% of total P was soluble organic P compared to 16% in the post-BMP period. The reduction in soluble organic P resulted in increases in inorganic forms of P. The proportion of P in the soluble inorganic form (orthophosphorus P) increased from 16% in the pre-BMP period to 46% in the post-BMP period for the A watershed.

For subwatershed C, a major increase in the proportion of P in the form of soluble organic P and orthophosphorus P occurred, while a large reduction in the particulate portion of P was observed (fig. 4). In the pre-BMP period, 82% of P was in the particulate form with only 4% and 14% in the form of orthophosphorus P and soluble organic P, respectively. In the post-BMP period, however, the portion of total P in the particulate form was reduced to only 39% while the portion in the form of orthophosphorus P and soluble organic P increased to 22% and 40%, respectively. For subwatershed D, the proportion of P in the form of soluble organic P decreased from 17% in the pre-BMP period to 10% in the post (fig. 4). Like watershed A and subwatershed C, the portion of total P in the particulate form was reduced, but the change in the portion was smaller for subwatershed D (from 68% to 59%). These reductions in soluble organic and particulate P resulted in an increase in the portion of orthophosphorus P. The proportion of total P contributed by orthophosphorus P more than doubled; increasing from 15% in the pre-BMP period to 31% in the post-BMP period for subwatershed D.

As with the increase observed for the proportion of soluble N, there are both benefits and drawbacks to the increases in the soluble forms of P. The main benefit is that the soluble forms of P are available to plants, thus nutrient value of the manure may increase. The drawback is that these same soluble forms of P also promote the growth of aquatic plants and algae, thus increases in the proportions of soluble P may increase the potential for degradation of the aquatic habitat in the receiving waters. This is especially true for orthophosphorus P, which is highly mobile and is a key nutrient in eutrophication. In the post-BMP periods, the average annual flow-weighted total P concentrations (table 3) exceeded the eutrophication standard of 0.10 mg L^{-1} total P concentration for streams not discharging directly into lakes (USEPA, 1986).

N:P Ratio and Eutrophication

The ratio of nitrogen to phosphorus (N:P) in water can help determine which nutrient will limit or control phytoplankton growth in water bodies (Redfield, 1958). The N:P ratios for different species of phytoplankton varies between 10 and 17 (Smith, 1982; Hecky and Kilham, 1988). Early studies by Sakamoto (1966) later confirmed by Forsberg (1981) suggested that the growth of phytoplankton may be N limited when the N:P ratio drops below 10, and P limited when N:P ratios exceed 17. For intermediate values of N:P (between 10 and 17) phytoplankton growth could be limited by either N or P.

Pre-BMP N:P ratio for watershed A was 7.24. A ratio this small obviously indicates N limitation for phytoplankton production. BMP implementation increased this ratio to 10.21 indicating that N or P limitations could occur depending on the phytoplankton species present in the downstream waters. The pre-BMP N:P ratios at station C (16.15) were also in this intermediate range, but dropped to 9.66, which is in the N limiting range, after BMP implementation. The N:P ratios at station D did not change much after BMP implementation. Both before (9.43) and after BMP implementation (9.54), the N:P ratios for subwatershed D remained in the N limiting range. These N:P ratios observed for Owl Run watershed are much lower than those reported by Jordan et al. (1997b) for Piedmont watersheds in Maryland and Pennsylvania. Jordan et al. (1997b) reported ratios ranging from 28 to 200. The difference between the ratios reported by Jordan et al. (1997b) and the ratios observed at Owl Run may result from differences in soils, landuse, and agricultural systems.

Since algae have the ability to fix nitrogen from the atmosphere, and atmospheric deposition of N is typically high for the Piedmont region, availability of N should not constrain phytoplankton growth. This is a cause of concern, because it would suggest that discharges of nutrients from Owl Run have a potential for causing eutrophication. The problem lies especially with elevated levels of bioavailable P discharged from the watershed. This suggests that although BMPs implemented on Owl Run were effective in controlling N, additional efforts need to be made to control the release of P.

Conclusions

The results of the 10-year study conducted in the Owl Run watershed clearly indicate the beneficial impacts of the BMPs on improving surface water quality. The main objective of the study was to determine the effectiveness of a system of animal waste BMPs for improving surface water quality. Some of the BMPs implemented as a part of the study included animal waste storage structures, N-based nutrient management, stream fencing, and water troughs.

Reductions in both N and P were observed due to the implementation of BMPs. A small increase was observed in precipitation amounts in the post-BMP period and corresponding increases were observed in streamflow. Even with the increases in streamflow, reductions of over

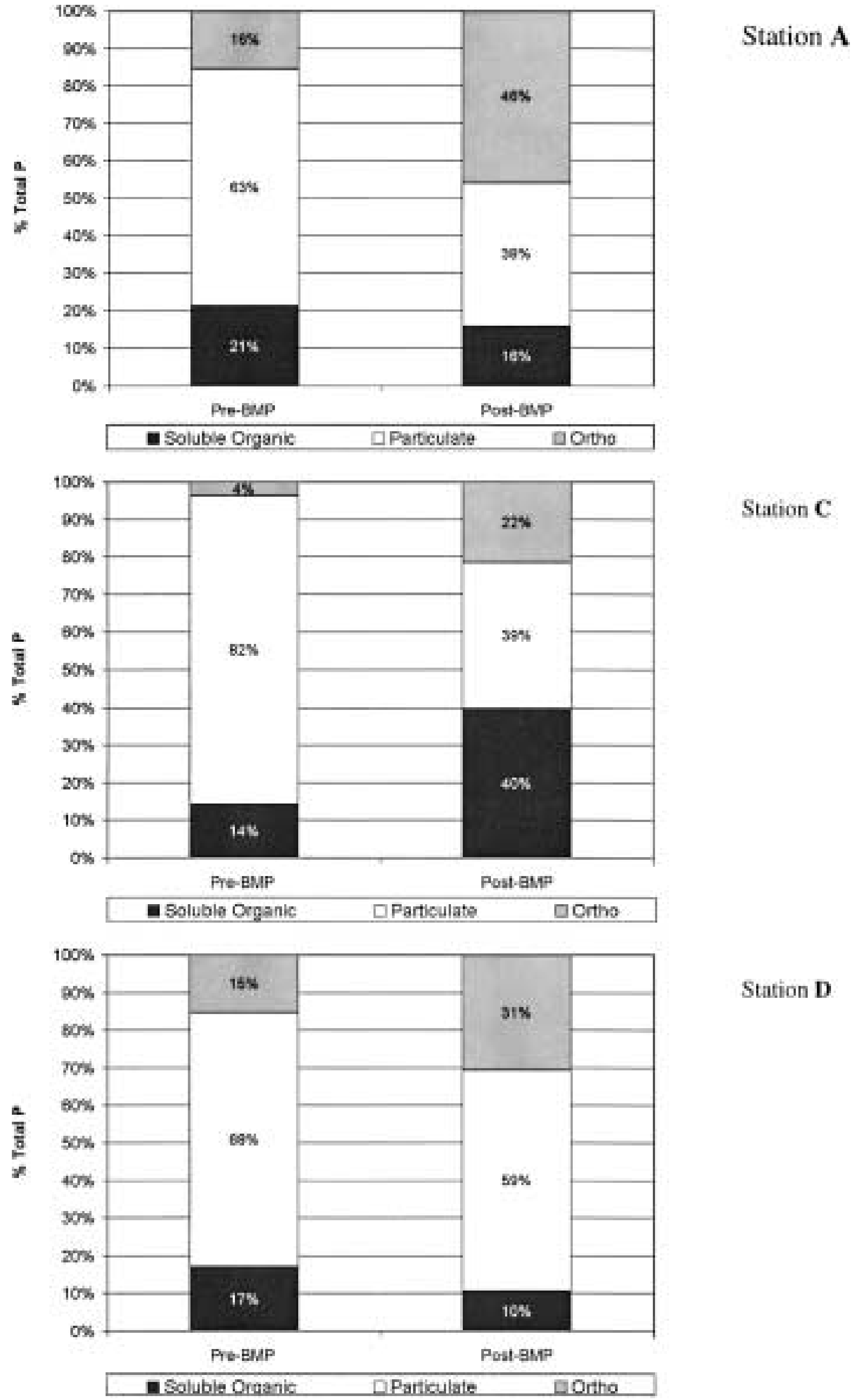

Figure 4–Proportions of total-P by species at stations A, C, and D.

40% were detected in monthly flow-weighted concentrations. Reductions in sediment, all forms of N, and most forms of P were observed in the average annual values due to BMP implementation. Specifically for the main watershed outlet (station A):

- BMPs reduced sediment load and concentration from the entire watershed by 19% and 35%, respectively.
- BMPs were effective in reducing both loads and concentrations of all forms of N with the largest reductions observed in soluble organic N

concentration (62%) and the smallest reduction for nitrate N concentration (35%).

- BMPs were effective in reducing both loads and concentrations of most forms of P with the largest reductions observed in particulate P concentration (78%) and the smallest reduction for soluble P concentration (39%).
- Orthophosphorus-P concentration increased by 7% after BMP implementation.

It appears that although the organic and particulate N and P loads and concentrations decreased due to BMP implementation, the proportion of bioavailable forms increased. The magnitude of dissolved ammonium N, nitrate N, and soluble organic N species leaving the main watershed decreased in the post-BMP period. However, the proportion of the total N that is bioavailable increased in the post-BMP period. The same was true for the particulate, organic and inorganic forms of P.

The increases in inorganic forms of N and P can be attributed to specific BMPs. For example, waste storage facilities allow for the conversion of organic forms of N and P to inorganic forms during storage. Similarly, increases in soluble forms of P may be the result of N-based nutrient management plans. The increase in the proportion of bioavailable forms of both N and P could result in excessive aquatic plant growth and algae blooms. Furthermore, the conversion of organic forms of N to inorganic through the process of ammonification and the loss of N to the atmosphere in the form of ammonia N could lead to increased atmospheric loading of N. The system of BMPs implemented in the Owl Run watershed were effective in reducing nutrient loadings, especially N loadings. However, possible increases in bioavailable P indicates that P-based nutrient management plans should be considered where P is the major water quality concern.

ACKNOWLEDGMENTS. This study was supported, in part, by funds provided by the Virginia's Department of Conservation and Recreation, Division of Soil and Water Conservation, Richmond, Virginia.

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