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A LONG-TERM, WATERSHED-SCALE, EVALUATION OF THE IMPACTS OF ANIMAL WASTE BMPs ON INDICATOR BACTERIA CONCENTRATIONS[1]

Shreeram P. Inamdar, Saied Mostaghimi, Mary Nicole Cook,
Kevin M. Brannan, and Phil W. McClellen[2]

ABSTRACT: Driven by increasing concerns about bacterial pollution from agricultural sources, states such as Virginia have initiated cost sharing programs that encourage the use of animal waste best management practices (BMPs) to control this pollution. Although a few studies have shown that waste management BMPs are effective at the field scale, their effectiveness at the watershed scale and over the long term is unknown. The focus of this research was to evaluate the effectiveness of BMPs in reducing bacterial pollution at the watershed scale and over the long term. To accomplish this goal, a 1,163 ha watershed located in the Piedmont region of Virginia was monitored over a ten-year period. Fecal coliforms (FC) and fecal streptococci (FS) were measured as indicators of bacterial pollution. A pre-BMP versus post-BMP design was adopted. Major BMPs implemented were manure storage facilities, stream fencing, water troughs, and nutrient management. Seasonal Kendall trend analysis revealed a significant decreasing trend during the post-BMP period for FC concentrations at the watershed outlet, but not at the subwatershed level. Implementation of BMPs also resulted in a significant reduction in the geometric mean of FS concentrations. FC concentrations in streamflow at the watershed outlet exceeded the Virginia primary standard 86 and 74 percent of the time during pre-BMP and post-BMP periods, respectively. Corresponding exceedances for the secondary standard were 50 and 41 percent. Violations decreased only slightly during the post-BMP period. The findings of this study suggest that although BMP implementation can be expected to accomplish some improvement in water quality, BMP implementation alone may not ensure compliance with current water quality standards.

(KEY TERMS: nonpoint source pollution; watershed management; water quality; bacterial pollution; fecal coliform; fecal streptococcus; BMP.)

INTRODUCTION

Contamination from bacterial sources has been identified as the third leading cause of pollution in the nation's rivers, after siltation and nutrients (USEPA, 1999). Pollution from bacteria accounts for nearly 79,820 impaired river miles or 12 percent of the total river miles surveyed in the United States (USEPA, 1999). In Virginia, fecal contamination of surface waters is the leading pollution problem, and agriculture has been cited as the largest contributor of this pollutant (USEPA, 1999). Land application of animal wastes and runoff from livestock facilities are the major agricultural practices contributing to bacterial pollution (Crane *et al.,* 1983; Baxter-Potter and Gilliland, 1988). State cost-sharing programs, such as the one in Virginia, have initiated voluntary animal waste Best Management Practices (BMPs) in an effort to reduce pollution from livestock operations (DCR, 1991). Recommended animal waste BMPs include storage of animal waste in containment structures and land application of manure during more favorable conditions, stream fencing, and buffer strips (DCR, 1991).

Although several studies and reviews have evaluated bacterial pollution from agricultural lands (Kunkle, 1970; Doran and Linn, 1979; Jawson *et al.,* 1982; Crane *et al.,* 1983; Baxter-Potter and Gilliland, 1988; Niemi and Niemi, 1991; Edwards *et al.,* 1997), only a few have investigated the impacts of BMPs. The studies that have investigated BMPs have generally been plot or field scale, short in duration, and have yielded mixed or inconclusive results (McCaskey *et al.,* 1971; Stephenson and Street, 1978; Doran and Linn, 1979; Patni *et al.,* 1985). Patni *et al.* (1985) found that storage of manure prior to application reduced indicator bacteria concentrations by more

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[2] Respectively, Assistant Professor, Great Lakes Center and Department of Geography, SUNY College at Buffalo, 1300 Elmwood Avenue, Buffalo, New York 14222; and H.E. and Elizabeth F. Alphin Professor, Former Graduate Student, Research Associate, and Former Watershed Project Manager, Biological Systems Engineering, 208 Seitz Hall, Virginia Tech, Blacksburg, Virginia 24061-0303 (E-Mail/Mostaghimi: smostagh@vt.edu).

that 99 percent, but they also reported no significant difference in bacterial pollution from runoff from manured and nonmanured cropland. Stephenson and Street (1978) observed reductions in indicator fecal coliforms (FC) after streambank fencing and cattle removal measures were introduced, but they were unable to clearly attribute the FC reductions to implementation of these management practices. Similarly, research on the effectiveness of buffer strips and vegetative filters has produced conflicting results (Jenkins *et al.,* 1978; Peters and Lee 1978; Hunt *et al.,* 1979). Crane *et al.* (1983), summarizing the work of Johnson and Moore (1978), suggested that filter strips were only effective in removing bacteria when subjected to high incoming concentrations [> 10^5 colony-forming units (cfu) per 100 mL].

Some of the reasons for these inconclusive or mixed results from BMP studies include: (a) the short-term and small-scale nature of these studies that provide limited information; and (b) environmental conditions that alter bacterial response. Environmental conditions that can influence bacterial populations include: variations in streamflow (Stephenson and Street, 1978; Tiedemann *et al.,* 1988; Edwards *et al.,* 1997); seasonal changes (Doran and Linn, 1979; Doran *et al.,* 1981; Jawson *et al.,* 1982; Howell *et al.,* 1995; Edwards *et al.,* 1997); and background concentrations (Hollon *et al.,* 1982; Niemi, 1991; Blevins *et al.,* 1995; Niemi and Howell *et al.,* 1995).

The goal of this study was to investigate the impacts of BMP implementation on bacterial pollution over the long term. Furthermore, unlike plot and field-scale studies, a major objective of this research was to determine the impacts of BMPs at the watershed scale. Specific objectives of this study were to: (1) characterize the ambient water quality of the watershed, with particular emphasis on the bacteriological aspects; and (2) investigate the impact of animal waste BMPs in reducing the losses of fecal coliforms (FC) and fecal streptococcus (FS) bacteria to surface water.

METHODS AND MATERIALS

Site Description

The Owl Run watershed was selected for a 10-year monitoring project starting in 1986. The watershed is located within Fauquier County, Virginia, approximately 65 km southwest of Washington, D.C. Fauquier County is situated in both the Piedmont and Blue Ridge Mountains physiographic regions of Virginia. The greater part of the county's terrain is steep and rugged. This part of the United States experiences a humid, continental type climate, with typically hot, humid summers and relatively mild winters. Average annual rainfall is approximately 1,040 mm, the majority of which occurs during the spring and is fairly well distributed throughout the county (Mostaghimi *et al.,* 1989). Except for the dry period during summer, when the streams tend to dry out, streamflow occurs for most of the year. During summer, streamflow is often generated by intense storm events.

Soils within the watershed are mostly shallow (0.3 to 0.6 m) silt loams, overlying Triassic shale. Approximately 72 percent of the soil series within the watershed are made up of the Penn (40 percent), Bucks (16 percent), and Montalto (16 percent) associations (NRCS, 1956). More than 60 percent of the Owl Run watershed is used in agricultural production, including both cropping and livestock productions (Table 1). The remainder of the watershed includes residential, commercial, transportation, and forested areas. About 31 percent of the watershed area is in cropland; approximately 18 percent is in pasture; woodland covers 26 percent of the area; and nonagricultural land, including streams, riparian, and wetland areas, constitute 10 percent (Table 1). The watershed supports five major dairies, one replacement heifer operation, and three small cattle operations. When the project was initiated, only one of the five dairies was using any type of waste management practice. The livestock numbers increased by 2 percent during the monitoring period. This increase occurred only in the dairy operations, as the beef operations experienced a slight decline in numbers over the course of the investigation. Five waste storage structures were designed and installed as BMPs as a part of this study. The locations of the various waste structures in the watershed are identified in Figure 1. Prior to the installation of the waste storage structures, farm operators land applied the material on a daily or weekly frequency.

Monitoring System

Four streamflow monitoring stations (QOA, QOB, QOC, and QOD) were established in the Owl Run watershed (Figure 1). Station QOA was located at the outlet of the Owl Run watershed (1,163 ha) and represented the overall response of the watershed. Station QOB drained a subwatershed of 45 ha and recorded urban runoff from the town of Calverton, Virginia (Figure 1). Station QOC captured agricultural runoff from a 462 ha subwatershed and was installed to demonstrate the effectiveness of cropland BMPs. Station QOD measured runoff from a 331 ha

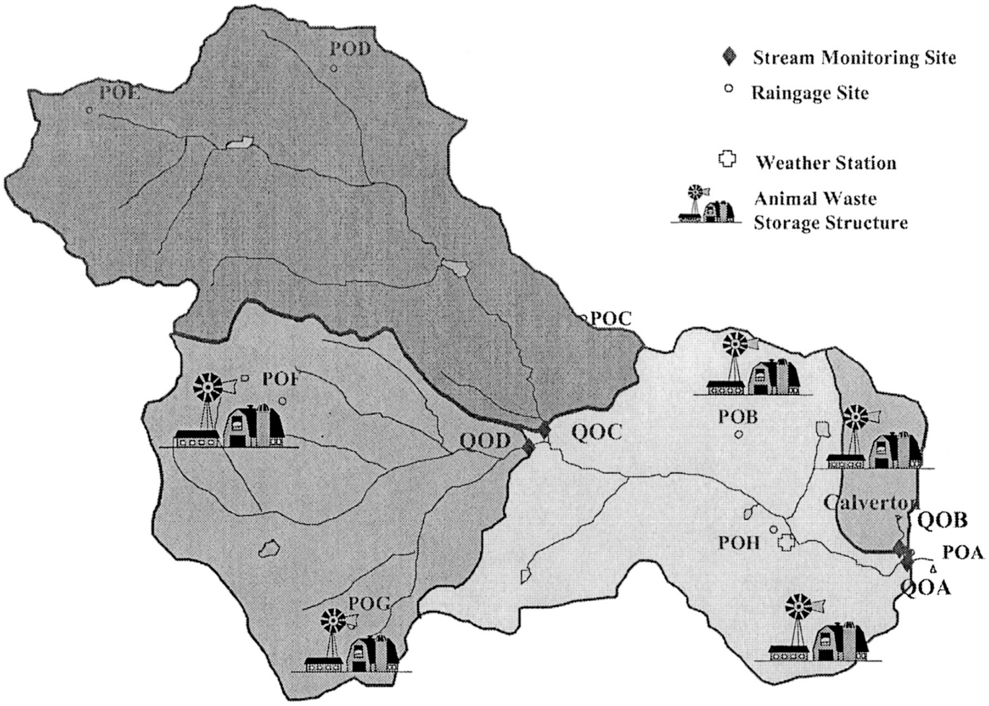

Figure 1. Location of Streamflow and Rainfall Monitoring Stations and Waste Storage Facilities in the Owl Run Watershed.

subwatershed, which included two of the five dairy operations within the Owl Run watershed. Monitoring station QOD was used to evaluate the effectiveness of intensive animal waste BMP implementations on stream water quality (Mostaghimi *et al.,* 1989). Streamflow was measured using stage recorders and data loggers. Precipitation in the watershed was measured at eight stations (POA through POH, Figure 1) using rain gages.

Biological sampling was initiated at station QOA and QOB during August 1986 and in December 1986 for QOC and QOD. Biological monitoring included "grab" sampling (twice a month) of stream water at the respective monitoring stations (Mostaghimi *et al.,* 1989). The "grab" water samples from streams were immediately put on ice and stored at 4°C. All bacteriological analyses occurred within 24 hours of sample collection, in accordance with APHA prescribed methods (APHA *et al.,* 1995). The Water Quality Laboratory at Virginia Tech performed the analysis for FC and FS bacteria. Testing of FS was conducted according to APHA's Method 910 (APHA *et al.*, 1985). Laboratory QA/QC procedures were developed and used for all sample analyses and data reduction procedures as prescribed by Mostaghimi (1989).

BMP Implementation

A pre-BMP versus post-BMP monitoring design was implemented. The pre-BMP period extended from August 1986 through June 1989. Implementation of BMPs was initiated in July 1989, and BMPs were gradually phased in. The post-BMP period was considered to extend from July 1989 to the end of the project in June 1996. A combination of structural and managerial BMPs was installed. Major structural BMPs included manure storage facilities, fencing, stream crossings, and watering troughs. Major managerial BMPs included conservation tillage, grassed waterways, and manure management. Manure management included storage of waste and its land application at an appropriate time and location. Waste storage structures (Figure 1) were designed to hold six months of manure produced at each facility. During the post-BMP period, land application of wastes occurred during the spring and fall. More than two-thirds of the stored waste was applied in April, while a significant portion was also applied in September. Prior to implementation of the waste storage facilities, the selection of fields for application of wastes was governed by their proximity to the facilities. However, after construction of storage facilities, the land operators had more flexibility in the choice of fields, with manure application being based on efficient utilization rather than accessibility. Most of the waste was land applied to croplands, which constituted approximately 35 percent of the overall land use area. Pastureland, which comprised roughly 25 percent of the watershed, also received a portion of the waste, through land application as well as directly from the grazing cattle. BMP implementation led to increased manure application on a unit area basis for subwatersheds QOC and QOD. However, the application rate for QOA watershed was reduced (Table 1). This suggests that watershed areas within QOA, but outside subwatersheds QOC and QOD, received considerably less manure application during the post-BMP period compared to the pre-BMP phase.

TABLE 1. Pre-BMP and Post-BMP Land Use and Management Activities in the 1,163 ha Owl Run Watershed.

		Pre-BMP	Post-BMP
Landuse in ha (percent values within brackets)			
Farmstead		25.2 (2)	21.1 (2)
Cropland		356.4 (31)	395.0 (34)
Nonagricultural		117.1 (10)	113.6 (10)
Forest		306.5 (26)	306.1 (26)
Pasture		209.3 (18)	266.7 (23)
Inactive Agricultural Land		44.6 (4)	36.0 (3)
Other*		103.9 (9)	24.5 (2)
Livestock			
Total Livestock Numbers		1,144	1,164
Manure Application			
Application Rate (m^3/ha/year)	QOA	38	22
	QOC	7	15
	QOD	19	32

*Other includes ponds, "no report," grassed waterways, and CRP conservation reserve program (CRP) land, as typically these land use categories were less than 5 percent of the watershed area.

Data Analyses

Pre-BMP and post-BMP values for streamflow (mm), FC (cfu/100mL), and FS (cfu/100 mL) were compared using both parametric and nonparametric statistical tests. Prior to performing the tests, geometric means for the FC and FS were grouped by "season" and the pre-BMP and post-BMP periods. Each year was partitioned into four "seasons," which included: winter, December through February; spring, March through May; summer, June through August; and fall, September through November. Since the exploratory tests (Shapiro-Wilk statistic, SAS Institute Inc., 1990) yielded a normal distribution for the log-transformed data and a nonnormal distribution for the untransformed geometric means, the log-transformed data were used for pre-BMP versus post-BMP statistical analysis. The "t" test was the parametric test used, whereas the Wilcoxon Rank Sum (WRS) test and the Kolmogorov-Smironov (KS) tests represented the nonparametric alternatives (SAS Institute, Inc., 1990). In addition to these tests, the Seasonal Mann-Kendall test (Gilbert, 1987; Helsel and Hirsch, 1993) was applied to the data to identify overall and seasonal trends for the pre-BMP and post-BMP periods. Seasonal Kendall test comparisons were performed by treating the pre-BMP and post-BMP data as two separate series. Pre-BMP and post-BMP trends were then quantified in terms of the Sen Slope values (Gilbert, 1987). The Sen method computes the slope as a change in the variable per-unit change in time and hence provides a quantitative measure for the trend in data.

BMP effectiveness was also evaluated by determining percent violations of Virginia State bacteria standards for the pre-BMP and the post-BMP periods. The primary contact standard for FC for the State of Virginia is set at a geometric mean of 200 cfu/100mL of water for two or more samples over a 30-day period (SWCB, 1992). The secondary contact standard for FC is set at a value of 1,000 cfu/100 mL, which may not be exceeded at any time (SWCB, 1992). To test against the primary standard, geometric means of FC concentrations were computed on a monthly basis when two or more samples were available during the month. Months with less than two samples were not included.

RESULTS AND DISCUSSION

Results from watersheds QOA, QOB, QOC, and QOD for precipitation, streamflow, FC, and FS are presented and discussed in the following paragraphs. Although BMPs were not implemented in watershed QOB, results from this watershed are included here for comparison with the other subwatersheds.

Precipitation

Annual rainfall totals for the pre-BMP (July 1986 to June 1989) and post-BMP (July 1989 to June 1996) periods are presented in Table 2. Average annual rainfall amount during the post-BMP period was 1.8 percent greater than the corresponding value for the pre-BMP phase. Annual rainfall during the pre-BMP years of 1987 and 1988 were below the annual average of 1,040 mm. The BMP transition year of 1989 recorded the highest annual rainfall of 1,278 mm. Except for 1991, annual rainfall for all years during the post-BMP period exceeded the long-term average. However, the "t," WRS, and KS tests on "seasonal" rainfall totals, did not reveal any significant differences between the pre-BMP and post-BMP rainfall amounts.

Rainfall amounts during the pre-BMP period were highest during spring and lowest during summer (Table 2). In contrast, post-BMP rainfall was highest during summer and lowest during winter (Table 2). Post-BMP average summer rainfall total was 1.6 times the corresponding pre-BMP value. Post-BMP spring rainfall total was slightly less that the pre-BMP value, whereas fall and winter totals for the two periods were similar. Long-term rainfall trends for this region indicate that rainfall during summer typically occurs in the form of intense, short duration, convective storms. Daily rainfall plotted over the pre-BMP and the post-BMP periods confirm (plot not included here) that the watershed experienced a larger number of intense summer storms during the post-BMP period compared to the pre-BMP period (Mostaghimi *et al,* 1999).

Streamflow

In contrast to the small (1.8 percent) increase in annual rainfall between the pre-BMP and post-BMP periods, increase in streamflow was considerably greater. Compared to the pre-BMP values, post-BMP average annual streamflows increased by 29, 32, 35, and 13 percent for QOA, QOB, QOC, and QOD, respectively (Table 2). Streamflow for both pre-BMP and post-BMP periods was at its maximum during winter and spring and and at its minimum during the summer. Although post-BMP streamflows across all seasons were higher than their corresponding pre-BMP values, the difference between summer values was especially large (Table 2). The elevated streamflows during summer were the primary reason for higher streamflow amounts recorded during the post-BMP period. Post-BMP summer streamflow totals for the four watersheds ranged between nine and 90 times their corresponding pre-BMP values. Higher summer streamflows during the post-BMP period were most likely associated with the increased incidence of short-duration, high-intensity rainfall events during this period. The "t," WRS, and KS tests on monthly streamflow totals for QOA, QOB, and QOD did not yield any significant differences between pre-BMP and post-BMP values at a α level of 0.10. Only tests for QOC revealed a significant difference

TABLE 2. Rainfall and Streamflow Totals for Owl Run Watersheds.

Period	Pre-BMP	Post-BMP
Rainfall (mm)		
Average Annual	1,056	1,076 (1.8)*
Winter (December to February)	212	230
Spring (March to May)	298	274
Summer (June to August)	197	316
Fall (September to November)	271	266

Period	QOA Pre-BMP	QOA Post-BMP	QOB Pre-BMP	QOB Post-BMP	QOC Pre-BMP	QOC Post-BMP	QOD Pre-BMP	QOD Post-BMP
Streamflow (mm)								
Average Annual	353	456 (29)*	208	275 (32)*	290	391 (35)*	311	351 (13)*
Winter (December to February)	121.9	185.9	80.5	107.3	87.1	165.2	101.1	146.6
Spring (March to May)	146.2	150.8	69.9	76.8	127.0	139.8	122.0	117.8
Summer (June to August)	4.1	64.6	4.6	42.1	0.6	54.3	1.4	52.4
Fall (September to November)	47.0	64.5	31.8	54.4	29.3	42.4	38.3	45.9

*Values in bracket indicate percent post-BMP increase over the pre-BMP value.

between the pre-BMP and post-BMP streamflow totals (α = 0.10).

Fecal Coliform (FC)

Comparison of Geometric Means. Geometric means of FC concentrations for the pre-BMP and post-BMP periods are presented in Table 3. Mean FC concentrations for QOA and QOD were an order of magnitude greater than previously reported values for similar land uses, whereas QOC values were of the same order as those reported for pasture with manure application (FC approximately 180 to 310 cfu/100 mL; Edwards *et al.,* 1997). Patni *et al.* (1985) though, reported a wide range of mean FC concentrations, from 8 to 2,100 cfu/100 mL for manured and nonmanured cropland. FC concentrations for QOA were lower in the post-BMP period compared to pre-BMP levels. In contrast, all contributing subwatersheds display a post-BMP increase in FC concentrations (Table 3). An overall reduction of 44 percent was observed at the main watershed outlet (QOA), whereas FC concentrations increased by 77, 86, and 27 percent for QOB, QOC, and QOD, respectively (Table 3). The "t" (p = 0.17) , WRS (p = 0.20), and KS (p = 0.38) tests, though, did not support a significant decrease (at a a level of 0.10) in FC concentrations for QOA (Table 4). The "t" test (p = 0.10) showed a significant increase in post-BMP FC concentrations (at a α level of 0.10) for QOB, which was not supported by the WRS (p = 0.13) and KS tests (p = 0.28). For subwatersheds QOC and QOD, all three tests failed to show any significant change in FC concentrations (Table 4).

Highest FC concentrations during both the pre-BMP and post-BMP periods were recorded at the outlet of subwatershed QOB, which drained the residential community of Calverton, Virginia. Although BMPs were not implemented in subwatershed QOB, results from this watershed are included here, since: (a) discharge from QOB influenced the concentrations at the main outlet QOA, and (b) these values can be used for comparison with subwatersheds QOC and QOD. During the post-BMP period a newly opened restaurant in watershed QOB started discharging sewage into a drainageway, which contributed into the outlet at QOB. It is very likely the restaurant discharges contributed to some of the high values recorded at QOB during the post-BMP period. In the absence of high values from QOB, it is very likely that reductions for QOA could have been even greater.

Subwatershed QOC, which was primarily cropland, had the lowest FC concentrations compared to other subwatersheds during both the pre-BMP and post-

TABLE 3. Pre-BMP and Post-BMP Fecal Coliform (FC) and Fecal Streptococci (FS) Values for Owl Run Watersheds.

Parameter	QOA Pre-BMP	QOA Post-BMP	QOB Pre-BMP	QOB Post-BMP	QOC Pre-BMP	QOC Post-BMP	QOD Pre-BMP	QOD Post-BMP
FC								
n*	51	117	47	108	40	108	41	110
Geometric Mean	1,189	669	1,244	2,196	103	185	1,077	1,367
Percent Change	-44		77		86		27	
Minimum	3	20	15	200	2	20	10	20
Maximum	60,000	16,000	103,250	160,000	1700	16,000	81,000	160,000
FS								
n	50	133	52	124	43	125	41	126
Geometric Mean	2,354	566	2,015	836	531	211	1,302	702
Percent Change	-76		-58		-60		-46	
Minimum	8	11	40	9	8	2	14	9
Maximum	540,000	620,000	142,000	350,000	227,000	140,000	163,000	266,500
FC:FS								
	0.5	1.2	0.6	2.6	0.2	0.9	0.8	1.9

*Number of samples.

TABLE 4. p-Values Assigned to the Difference Between Pre-BMP and Post-BMP Geometric Means by Step Tests for Fecal Coliform (FC) and Fecal Streptococci (FS) for Each Watershed.

Watershed	FC			FS		
	"t"	WRS	KS	"t"	WRS	KS
QOA	0.1748	0.1959	0.3826	0.0078	0.0162	0.0914
QOB	0.0985	0.1277	0.2788	0.0832	0.0531	0.1496
QOC	0.2768	0.2010	0.2125	0.0311	0.0352	0.1795
QOD	0.9755	0.8550	0.9748	0.1426	0.2019	0.5210

BMP periods. Subwatershed QOC also contained a pond on the main drainage stem of the watershed (Figure 1). It is possible that the low FC concentrations recorded for QOC were influenced by the pond. FC concentrations recorded for QOD were intermediate of those recorded for QOC and QOB.

Seasonal geometric means for FC from the pre-BMP and post-BMP periods are presented in Table 5. Post-BMP FC concentrations for QOC were greater than the corresponding pre-BMP values across all the seasons. Compared to the pre-BMP levels, post-BMP FC concentrations from watershed QOD decreased for spring and fall but increased for winter and summer. Waste application during the pre-BMP period typically occurred on a daily or weekly basis, whereas during the post-BMP period it was restricted to the spring and autumn months, with the waste being stored for the remaining months. Based on this application

TABLE 5. Seasonal Fecal Coliform (FC) and Fecal Streptococci (FS) Geometric Means for Owl Run Watersheds.

Parameter	Winter		Spring		Summer		Fall	
	Pre-BMP	Post-BMP	Pre-BMP	Post-BMP	Pre-BMP	Post-BMP	Pre-BMP	Post-BMP
QOA								
n*	16	36	16	34	7	24	12	23
FC	966	582	2,208	753	566	1,105	1,059	414
n	15	38	17	39	7	27	11	29
FS	7,127	467	1,755	299	997	864	1,415	1,166
FC:FS	0.1	1.2	1.3	2.5	0.6	1.3	0.7	0.4
QOB								
n	15	37	16	33	6	19	10	19
FC	1,013	3,214	2,056	1,933	747	1,436	1,030	1,999
n	16	37	18	33	8	25	10	26
FS	1,810	880	1,543	676	3,599	822	2,434	1,065
FC:FS	0.6	3.7	1.3	2.9	0.2	1.7	0.4	1.9
QOC								
n	11	34	18	36	6	21	5	17
FC	66	128	140	232	89	312	106	157
n	12	37	19	40	6	25	6	23
FS	530	188	546	125	259	337	1000	383
FC:FS	0.1	0.7	0.3	1.9	0.3	0.9	0.1	0.4
QOD								
n	13	34	16	33	6	21	6	22
FC	654	978	2,731	1,959	114	1,189	2,506	1,531
n	13	38	17	39	7	25	4	24
FS	2,074	763	1,802	460	202	912	1,881	929
FC:FS	0.3	1.3	1.5	4.3	0.6	1.3	1.3	1.6

*Number of samples.

schedule, one would expect post-BMP FC concentrations to be lower than the corresponding pre-BMP values during winter and summer. Likewise, significant post-BMP reductions in fecal bacteria concentrations during spring and autumn were not expected. Alternately, if storage of waste results in attenuation of FC and FS concentrations as reported by Patni *et al.* (1988), it is likely that some reductions in fecal bacteria concentrations could occur during spring and autumn. In light of these expectations, the increase in post-BMP FC concentrations during winter for QOC and QOD were unexpected. FC concentrations had a weak negative correlation with streamflow, and thus the post-BMP winter increase in FC could not be directly attributed to post-BMP streamflow increases. This suggests the likelihood of alternate or background sources of fecal coliform, such as wildlife. Sherer *et al.* (1992) have reported the persistence of bacteria in stream sediments.

Compared to pre-BMP levels, the annual amounts of manure application to watersheds QOC and QOD were more during the post-BMP period (Table 1). Hence, despite the more intense post-BMP waste application during spring, the lower FC concentrations observed from QOD during this period would then tend to suggest some attenuation of fecal bacteria while in storage. Although this same argument should also be applicable to QOC, the increased FC concentrations in the spring do not lend support. It should be noted, though, that QOC FC concentrations were nearly an order of magnitude less than QOD values.

Post-BMP FC concentrations at the main watershed outlet QOA were less than their pre-BMP values across all seasons, except in summer (Table 5). Post-BMP summer FC concentrations for QOA were nearly double their pre-BMP level. The other subwatersheds too, display a similar increase in post-BMP summer FC concentrations over their pre-BMP levels. Occurrence of high bacterial populations during the warm summer months has been reported in previous research (Doran and Linn, 1979; Doran *et al.,* 1981; Jawson *et al.,* 1982; Edwards *et al.,* 1997). For Owl Run watersheds, one likely reason for the higher post-BMP summer values could be the higher level of hydrologic activity during the post-BMP period. Even though FC concentrations were not correlated to streamflow, the larger number of high-intensity rain events during the summer post-BMP periods likely provided a greater opportunity for bacteria to be flushed from the contributing land surface.

Trend Analysis. Seasonal geometric means of FC concentrations for all the watersheds are presented in Figures 2 through 5. These plots provide a good visual feel for the trend in bacteria concentrations over the pre-BMP and post-BMP periods. Trend analysis results from Seasonal Kendall tests (Table 6) reported a significant difference between overall trends for pre-BMP and post-BMP FC concentrations for QOA at a α level of 0.10 (p = 0.001). The pre-BMP FC concentrations followed a significant increasing trend with a Sen slope of 1,397 cfu/100mL, whereas the post-BMP period exhibited a significant decreasing trend with a

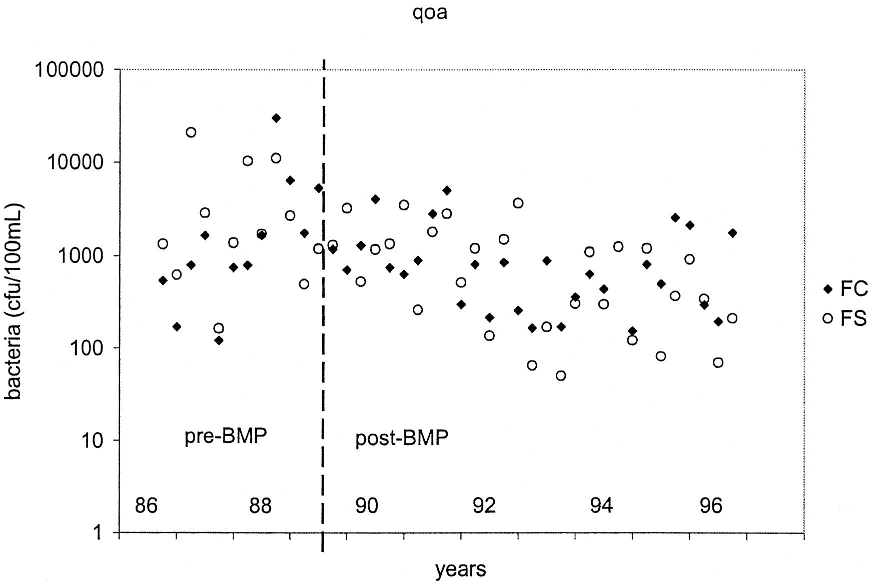

Figure 2. Seasonal Geometric Means for FC and FS for Watershed QOA.

negative Sen slope of 115 cfu/100mL (Figure 2). Although no significant seasonal trend was observed (p = 0.88) for the QOA data, pre-BMP seasonal Sen slopes were all positive, whereas post-BMP seasonal slopes, with the exception of summer, were all negative.

For QOB, there was no significant difference between the overall trends for the pre-BMP and post-BMP periods (p = 0.17). Both pre-BMP and post-BMP periods displayed increasing trends, with the pre-BMP Sen slope value (824 cfu/100mL) being much greater than the post-BMP value (55 cfu/100mL) (Figure 3). Similar to QOA, there was no significant seasonal trend in QOB FC data.

Post-BMP FC values for QOC had a nonsignificant increasing overall trend given by a Sen slope value of 12 cfu/100mL (Figure 4). There were no significant seasonal trends in FC concentrations for QOC.

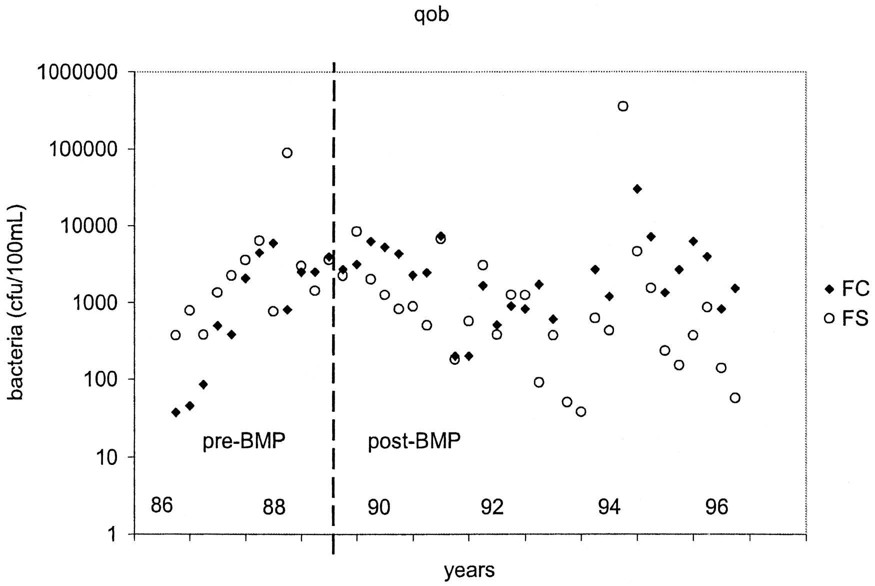

Figure 3. Seasonal Geometric Means for FC and FS for Watershed QOB.

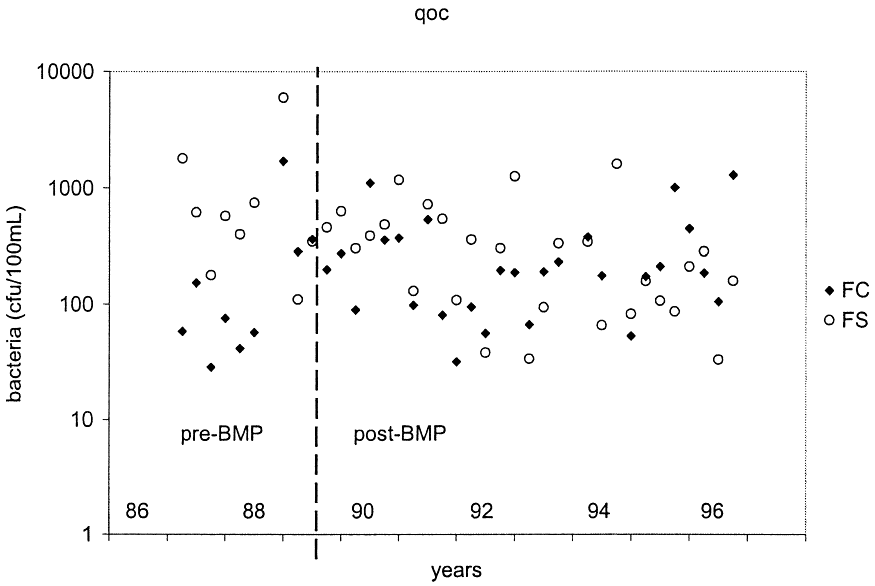

Figure 4. Seasonal Geometric Means for FC and FS for Watershed QOC.

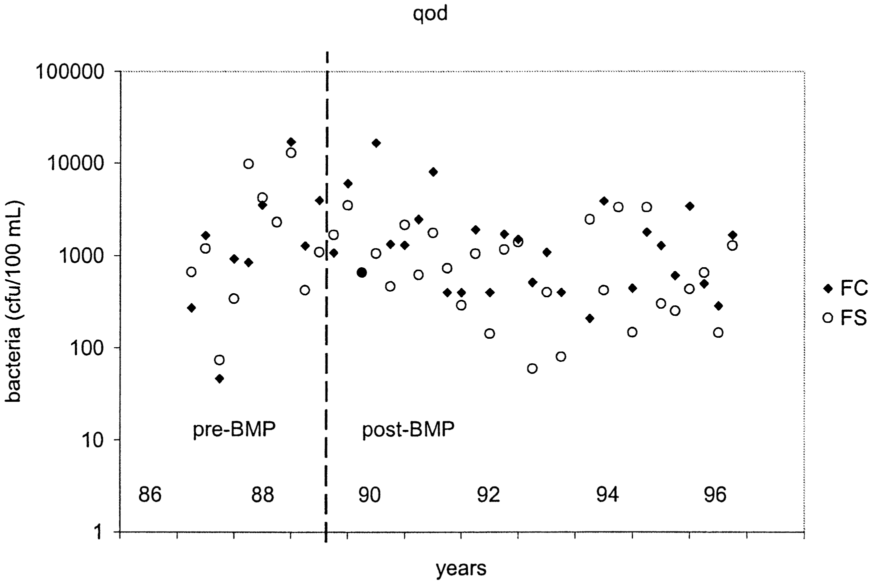

Figure 5. Seasonal Geometric Means for FC and FS for Watershed QOD.

Seasonal Sen slopes for QOC data were positive for all seasons except spring, which had a nonsignificant decrease. Similarly to QOC, the overall trend of FC values for QOD was nonsignificant, but unlike QOC and QOD, FC values decreased through the post-BMP period with a Sen slope of -157 cfu/100mL (Figure 5). Seasonal trends for QOD were not significant, and except for summer, all seasons had negative Sen slope values (Table 6).

The results from step tests ("t," WRS, and KS tests) and Seasonal Kendall trend tests provide for some interesting comparisons. Step test ("t," WRS, and KS tests) results indicated that BMP implementation did not result in a significant reduction of FC concentrations. In contrast, seasonal Kendall tests suggest that overall pre-BMP and post-BMP trends for QOA are not only significantly different but also have different slope directions. Interpretation of these results requires consideration of the project duration and the expected time frame for BMP impacts to occur. Previous research has shown that improvement in water quality in response to BMP implementation is not immediate and could require as long as 20 to 30 years to occur (Spooner *et al.,* 1985). This will especially be true for large watersheds with multiple land uses where several environmental factors are expected to influence the water quality variable of interest. Moreover, watershed-scale BMP implementation is rarely instantaneous and will typically occur over a period of months or years. If BMPs are phased in over months or years, it is very likely that water quality improvements will be gradual and will have some time lag associated with them. Under such conditions, it is highly unlikely that a few years of data will produce significant differences from step tests. For such studies, trend analysis procedures are more likely to discriminate and report any gradual differences between pre- and post-BMP periods. These arguments appear to be applicable to a large watershed like Owl Run, where BMPs were gradually implemented. Hence, in light of these considerations, it seems that Owl Run trend analysis results should be weighed in favor of results from step tests. It is important, though, that if trend tests are to be favored, both step and trend tests should show some general agreement and not contradict each other. If the tests contradict each other, additional data evaluation is necessary.

Pre-BMP Versus Post-BMP Evaluation Against Virginia State Standards. Results presented in Table 7 show that percent violations of the primary and secondary standards were considerably high for both pre-BMP and post-BMP periods across all watersheds. Moreover, for subwatersheds QOC and QOD, the percent violations increased despite BMP implementation. Only at QOA was a slight reduction in percent violations after BMP implementation observed. To investigate the seasonal distribution of these violations, percent violations for the secondary contact standard were computed for each season and are reported in Table 8. From Table 8 it appears that, in general, more than half the violations (considering pre-BMP and post-BMP periods) typically occurred during winter and spring seasons. The increase in violations during the post-BMP period, though, especially for QOC and QOD, was largely due to increased

TABLE 6. Seasonal Kendall Test Results for Pre-BMP and Post-BMP Fecal Coliform (FC) and Fecal Streptococci (FS) in the Owl Run Watersheds (p values are for the difference between pre-BMP and post-BMP overall and seasonal time series; and Sen slopes quantify the slopes of the time series).

	p-Values		Sen Slopes (cfu/100mL)			
			Overall Station Trend		Seasonal Trend	
Watershed	**Overall Station Trend**	**Seasonal Trend**	**Pre-BMP**	**Post-BMP**	**Pre-BMP**	**Post-BMP**
			FC			
QOA	0.001	0.881	1397	-115	474, 1,846, 14,730, 3,149	-118, -521, 49, -51
QOB	0.170	0.782	824	55	1,198, 1,708, 384, 1,222	176, -521, -163, 624
QOC	–	0.358	–	12	–	16, -186, 134, 7
QOD	–	0.149	–	-157	–	-112, -1,703, 51, -212
			FS			
QOA	0.242	0.290	-677	-154	-10,206, -835, 4,882, 1,038	16, -183, -172, -387
QOB	0.006	0.692	1490	-185	519, 1,119, 44,203, 1,092	-93, -185, -131, -284
QOC	–	0.846	---	-31	–	-3, -56, -52, -70
QOD	–	0.268	–	-85	–	198, -151, -7, -500

TABLE 7. Pre-BMP Versus Post-BMP Violations of Virginia Primary and Secondary Fecal Coliform Standards.

	Geometric Mean Greater Than 200 cfu/100mL Within 30 Days (Primary Standard)		Greater Than 1,000 cfu/100 mL at Any Time (Secondary Standard)	
Watershed	**Pre-BMP Violations (percent)**	**Post-BMP Violations (percent)**	**Pre-BMP Violations (percent)**	**Post-BMP Violations (percent)**
QOA	86	74	50	41
QOB	84	97	56	61
QOC	29	48	4	18
QOD	79	94	47	48

TABLE 8. Pre-BMP and Post-BMP Percent Violations of the Virginia FC Secondary Standard (> 1000 cfu/100 ml at any time) by Season.

	Winter Violations (percent)		Spring Violations (percent)		Summer Violations (percent		Fall Violations (percent	
Watershed	**Pre-BMP**	**Post-BMP**	**Pre-BMP**	**Post-BMP**	**Pre-BMP**	**Post-BMP**	**Pre-BMP**	**Post-BMP**
QOA	27	27	38	31	4	29	31	14
QOB	37	39	33	27	11	16	19	18
QOC	0	16	50	42	0	21	50	21
QOD	25	29	55	35	5	17	15	19

violations during the summer. These results are in contrast to Edwards *et al.* (1997) who found most violations of the primary and secondary contact standards occurred during summer and spring.

Pre-BMP and post-BMP evaluations of the FC concentrations against the Virginia State Standards do not appear to be encouraging. Despite implementation of BMPs, violations for QOC and QOD increased during the post-BMP period. Although FC concentrations at QOC were the lowest of all the watersheds monitored, percent violations of the primary and secondary standards still varied between 4 and 48 percent. Similarly, although there was a post-BMP reduction in FC concentrations at the main watershed outlet (QOA), the percent violations still exceeded the permissible limits. These results lend support to previous studies that have found similar violations and have questioned the appropriateness of applying standards that were primarily developed for point source control to diffuse agricultural sources of bacterial pollution (Doran and Linn, 1979; Doran *et al.,* 1981; Jawson *et al.,* 1982; Howell *et al.,* 1995).

Fecal Streptococcus (FS)

Comparison of Geometric Means. Compared to FC, there was much larger variability in FS values during both the pre-BMP and post-BMP periods. Similar to that for FC, FS concentrations from cropland subwatershed QOC were the lowest, with high values from QOB and QOA. Mean FS concentrations for QOC exceeded reported values for other pasture watersheds with manure application (FS approximately 150 to 360 cfu/100mL; Edwards *et al.,* 1997). However, Patni *et al.* (1985) also reported a much wider range of FS concentrations, varying from 46 to 3,700 cfu/100 ml from manured and nonmanured cropland.

A comparison of FS geometric means for the pre- and post-BMP periods shows a post-BMP decrease across all watersheds. Reductions in FS values occur even for subwatersheds QOB, QOC, and QOD where post-BMP increases in FC were reported. Again, unlike the results observed for FC, "t," and WRS, step tests indicated that the decrease in FS concentrations was significant for all watersheds except QOD (Table 4). Geldreich (1976) has reported that FS strains derived from animals, particularly cattle and horses, are less persistent than FC and are more likely to die off with time. Considering this information, it is possible that storage of manure prior to land application provided an opportunity for preferential die-off of FS strains derived from cattle feces and thus contributed to the post-BMP decrease in FS concentrations.

During the pre-BMP period, FS concentrations were generally high for the winter, spring, and fall seasons at QOA, QOC, and QOD. During the post-BMP period, FS concentrations for these seasons dropped to less than half their pre-BMP values. It is likely that manure storage prior to application was responsible for some attenuation. Subwatersheds QOC and QOD registered an increase in post-BMP FS concentrations during the summer. Seasonal FS trends did not necessarily conform with seasonal FC trends. Edwards *et al.* (1997) reported that both FC and FS concentrations were highest during the summer and lowest during the winter and fall. For Owl Run watersheds, although FC concentrations tended to be higher during the summer, especially during the post-BMP phase, this propensity was not that apparent for FS.

Trend Analysis. The overall and seasonal trends in FS concentrations for QOA derived from seasonal Kendall tests were not significant at an α level of 0.10 (Table 6). But unlike FC, the Sen slope value for pre-BMP FS concentration for QOA indicated a decreasing trend (Sen slope = -677). This negative Sen slope value was primarily a result of a high FS concentration recorded during the early part of the pre-BMP period (value approximately 20,000 in Figure 2). Post-BMP FS concentrations for both QOC and QOD did not possess any significant seasonal trends. Overall trends during the post-BMP phase for both watersheds had nonsignificant negative Sen slopes, indicating an overall decreasing trend.

Fecal Coliform: Streptococci Ratio

The ratio of fecal FC and FS has been used to determine the source of fecal pollution in surface waters (Geldreich *et al.,* 1968). Use of this parameter as an identifier for source of fecal pollution, though, has produced mixed results. Some researchers have reported success with this method (Doran and Linn, 1979; Doran *et al.,* 1981; Tiedemann *et al.,* 1988), while others have found it to be an unreliable indicator of the source of bacterial pollution (Edwards *et al.,* 1997). Typically, if the ratio has a value greater than 4, then the source of the fecal contamination is considered to be human; if the ratio is less than 0.6, then the source is likely nonhuman, warm-blooded animals. A ratio falling in the range of 0.1 to 0.6 is attributed to domestic animals, while below 0.1 is typical of wildlife (Geldreich *et al.,* 1968). Geldreich (1976), however, cautioned that FC:FS ratios might gradually shift with time because of differential die-off rates. FS strains from domestic waste are more persistent than FC, whereas the opposite is true for animal feces. Hence, it is also likely that FC:FS ratios between 0.7 and 3.0 may be indicative of fecal pollution from animal feces, particularly cattle and horse. In addition, Doran and Linn (1979) suggested that FC:FS ratios between 0.7 and 4.0 in runoff from pastures may indicate situations where cattle have been close to sampling or outflow points, introducing fresh feces in runoff.

The intent was to determine if the FC:FS ratios from the Owl Run watersheds conformed to the values reported in literature for different land uses. We did not expect any specific change in these ratios as a result of BMP implementation, since the primary land use within the watersheds remained unchanged. FC:FS ratios for the pre-BMP and the post-BMP periods for the watersheds are presented in Table 3. FC:FS ratios for QOA, QOC, and QOD varied from 0.2 to 1.9, which was in the neighborhood of the range of 0.7 to 3.0 suggested by Geldreich (1976) for fecal pollution from animals, particularly cattle and horses. Although ratios for QOB, which drained a residential community, were higher than those recorded for QOC and QOD (0.6 and 2.6 for pre-BMP and post-BMP periods, respectively), the values were not high enough to suggest human fecal material as a possible source.

SUMMARY AND CONCLUSIONS

The impact of animal waste BMPs on bacterial pollution were evaluated for a 1,163 ha mixed land use watershed located in Fauquier County, Virginia. The intent was to evaluate the impact of BMPs at the watershed scale and over the long term. The study period extended over a period of ten years, with the first three years comprising the pre-BMP phase and the remaining period representing the post-BMP phase. Implemented BMPs included manure storage facilities, fencing, stream crossings, watering troughs, nutrient management, conservation tillage, and grassed waterways. FC and FS concentrations were monitored at the outlet of the main Owl Run watershed (QOA) and three subwatersheds QOB, QOC, and QOD.

Post-BMP annual precipitation totals were 1.8 percent greater than the pre-BMP values. Step (“t,” Wilcoxon Rank Sum, and Kolmogorov-Smirnov) and seasonal Kendall tests did not reveal any significant differences between the pre-BMP and post-BMP precipitation. In comparison to precipitation, post-BMP increases in annual streamflow totals were much greater. On an average there was a 30 percent increase in streamflow across the four watersheds. Except for watershed QOC, increase in streamflow in the other watersheds was not statistically significant.

A reduction in post-BMP FC concentrations was observed at the main watershed outlet (QOA), but all monitored subwatersheds recorded increases in FC concentrations. The percent reduction at QOA was 44, whereas increases for QOC and QOD were 86 and 27 percent, respectively. Despite these changes, the step tests did not yield significant differences. In comparison, the seasonal Kendall test did register a significant difference between the overall trends for QOA pre-BMP and post-BMP periods. Seasonal trends that were expected as a result of BMP implementations were not observed for all the watersheds. We expected that post-BMP FC concentrations, especially during winter, would be lower than their pre-BMP values since waste was stored and not land applied. QOA winter FC concentrations were lower than their pre-BMP values, but QOC and QOD both showed post-BMP increases. Manure application that occurred year-round during the pre-BMP period was confined to the spring and fall months during the post-BMP period. Hence we did not expect major reduction during the spring and fall seasons. But results for QOA showed considerable reductions in FC for both spring and fall, and moderate reductions for QOD but increases in QOC FC values for both seasons. Post-BMP decrease in FC concentrations probably could be attributed to attenuation of bacterial populations while in storage. Post-BMP FC concentrations during summer were greater than their pre-BMP levels for all subwatersheds. We attribute this post-BMP increase in FC concentrations to the increased incidence of high-intensity summer events that likely provided a greater opportunity for bacteria to be flushed out of the watersheds.

Violations of Virginia primary and secondary fecal coliform standards were high during both pre-BMP and post-BMP periods. Although some reductions were observed at QOA, violations across other subwatersheds increased during the post-BMP period. These results lend support to previous studies that have found similar violations and have questioned the appropriateness of applying standards that were primarily developed for point source control to diffuse agricultural sources of bacterial pollution.

In comparison to FC, post-BMP reductions in FS concentrations were observed across all the watersheds. FS concentrations decreased by 76, 60, and 46 percent for QOA, QOC, and QOD, respectively. These reductions were reported as significant by step tests for all watersheds, except for QOD. The greater reductions in FS as compared to FC could have been due to the preferential die-off of FS bacteria during storage. The variable response displayed in FS and

FC concentrations over time and across the watersheds underscores the uncertainty involved in using these bacteria as indicators of fecal contamination.

Overall, although there were slight decreases in FC concentrations at the main watershed outlet and larger decreases in FS concentrations across all watersheds, definitive and consistent evidence of water quality improvement due to BMP implementation was not observed. This leads us to conclude that although BMP implementation can be expected to accomplish some improvement in water quality, BMP implementation alone does not ensure compliance with current water quality standards.

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