Impact of Animal Waste Best Management Practices on the Bacteriological Quality of Surface Water

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(ABSTRACT)

An extensive 10 year monitoring project was initiated in 1986 to examine the effects of a combination of BMPs on surface water quality within a watershed with complex land use. This research specifically examined bacteriological water quality and BMP impacts. Bimonthly grab samples were collected from four surface water monitoring stations, including the watershed outlet, and analyzed for fecal coliform, total coliform, and fecal streptococcus bacteria. Other data compiled from the watershed included hydrologic, meteorologic, geologic and land use data, also collected on a regular basis. Data were collected continuously throughout the project, and thus included both pre- and post-BMP monitoring data. BMP implementation included animal waste storage facilities, nutrient management plans, conservation tillage, alternative water sources for livestock, fences, vegetative filter strips, runoff diversions, and others.

Statistical analysis of the monthly precipitation data indicated no significant difference in rainfall quantity between the pre-BMP and post-BMP monitoring periods. Monthly runoff totals increased 39% from the pre- to the post-BMP periods at the watershed outlet. Increases at all of the subwatershed outlets occurred as well (B, 40%; C, 38%; D, 16%). Statistical analysis did not show a significant difference in runoff between the two monitoring periods, except at station C, where post-BMP runoff was significantly greater than the values measured during the pre-BMP period.

Overall reductions in the mean (geometric) levels of total coliform, fecal coliform and fecal streptococcus bacteria observed at the watershed outlet were 81%, 30% and 76%, respectively. Both parametric and nonparametric statistical analysis techniques were applied to the bacteriological data. Regression analysis of the fecal coliform data showed an increase during the pre-BMP period followed by a decrease post-BMP and a statistically significant difference between the two periods (p=0.004). No trends were evident. Only one of the four stations had a statistical difference between pre- and post-BMP fecal streptococcus data, however, a downward trend was present at every station. No statistically significant difference between the pre- and post-BMP total coliform bacteria was evident, although a downward trend was present at the watershed outlet. These findings indicate that the combination of BMPs implemented in the watershed were effective in reducing the loss of fecal bacteria to receiving streams via overland flow.

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Dedication

This work and all of its efforts are dedicated to my parents, Alexander B. Cook and Janet Saad-Cook, who each made very wonderful and very different contributions to my personal growth and development.

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Introduction

Civilization has always turned to bodies of water for sustenance—whether it be for food, drink, transportation or waste disposal. The downside of utilizing this essential resource is the occurrence of water contamination resulting from its many and varied uses. The Ancient Greek physician Hippocrates is first documented as advising that polluted water should be filtered and/or boiled before consumption (Gaudy & Gaudy, 1980). However, it is only within the last 150 years that society has been cognizant of diseases which could be spread using water as a vector. Mary Mallon was the infamous cook for a Long Island family during the first decade of the twentieth century. As an asymptomatic carrier of the organism *Salmonella typhi*, "Typhoid Mary" was single-handedly responsible for the outbreak of at least 200 cases of typhoid fever which she transmitted through the water used for drinking and cooking (Bullock & Maier, 1996). The story of Typhoid Mary is only one of the numerous instances throughout history in which the poor quality of potable water and a lack of sanitation has had a direct impact upon public health.

Over the past 25 years, the comprehensive efforts made to improve the water quality within the United States have been met with apparent success. The primary focus of these measures, however, has been water degradation caused by point sources. Section 502(14) of the Clean Water Act defines "point source" pollution as ". . .any discernible, confined and discrete conveyance, including but not limited to any pipe, ditch, channel, tunnel, conduit, well, discrete fissure, container, rolling stock, concentrated animal feeding operation, or vessel or other floating craft, from which pollutants are or may be discharged. This term does not include agricultural storm water discharges and return flows from irrigated agriculture."

By default, "nonpoint source" (NPS) pollution is loosely defined as anything which fails to fall within the point source definition. "NPS pollution generally results from land runoff, precipitation, atmospheric deposition, drainage, seepage, or hydrologic modification" (USEPA, 1993). Sources of NPS pollution include agriculture, forestry, hydromodification, onsite wastewater disposal, and construction sites (USEPA, 1997).

Under the Clean Water Act, point source discharges are subject to permit requirements along with being regulated by the United States Environmental Protection Agency (USEPA). Nonpoint sources, in contrast, have no such mandates. Thus, the seeming victory of point source control measures to improve water quality has a bittersweet reality as NPS pollution moves to the forefront as the Nation's leading cause of water quality impairments (USEPA, 1997).

Agriculture alone is the leading source of decreased water quality in both lakes and rivers, and the third largest contributor to estuarine habitat degradation (USEPA, 1997). Overland flow from agricultural lands can contain nutrients, sediments, pesticides, salts, and animal wastes. The effects of such materials entering into receiving waters include both decreased water quality as well as riparian habitat losses.

As livestock operations continue to expand, farm owners are constantly dealing with the issue of animal waste management. Livestock operators have been land applying manure for centuries in an effort to manage the large volumes of animal waste, as well as to reduce the amount of synthetic fertilizers that must be purchased and applied. Although the land operator may view this approach as a feasible method of managing the animal wastes while simultaneously saving money, this method could potentially cause both health and environmental problems. The bacterial contamination of surface waters receiving runoff from such lands is a major health concern (Crane et al, 1980).

In the Commonwealth of Virginia, the most extensive water quality problem of rivers and streams continues to be fecal contamination of surface waters, and agriculture is cited as the largest contributor of this pollutant (USEPA, 1998). In an effort to reduce the contamination potential of surface and ground waters by agricultural runoff, investigators have designed and adopted various best management practices (BMPs). However, the data available on the effectiveness of BMPs at the watershed level is lacking (Edwards et al., 1997c; Park et al., 1994). In order to justify the installation of BMPs, the effects of such measures should be known. Furthermore, if public funds are going to be used to subsidize BMP implementation and upkeep, then the impact of such measures should be documented in order to justify such an expenditure.

Comprehensive studies have been conducted at both the field and watershed levels in order to understand the presence of bacteria and its significance on nonpoint source pollution (Baxter-Potter & Gilliland, 1988; Crane et al., 1983; Niemi & Niemi, 1991). The majority of studies, however, focus on field-scale investigations. Field or plot studies are an attractive option for conducting research, as they are more easily accessible and more easily managed than larger-scale studies. However, these smaller-scale studies often have a narrower scope of investigation. For instance, a plot may only contain a single land used and test only one BMP. Researchers have concluded, however, that solitary management practices such as vegetative filter strips (VFS) are not sufficient in reducing bacterial contamination of the receiving waters (Coyne & Blevins, 1996; Walker et al, 1990). Clearly there is an inadequate amount of studies published as of now which document significant impacts at the watershed level. Therefore, it was the intention of this study to examine the effects of a combination of BMPs implemented throughout a watershed in order to improve the bacteriological quality of the surface waters receiving overland flow from agricultural operations.

Goals and Objectives

The overall goal of this study was to evaluate the effectiveness of animal waste management practices on improving the bacteriological quality of surface water.

Specific objectives to meet this primary goal included:

a) characterizing the ambient water quality of the study site, with particular emphasis on the bacteriological aspects

b) assessing the impact of animal waste BMPs in reducing the losses of fecal coliform, fecal streptococcus and total coliform bacteria to surface water.

Literature Review

The microbial contamination of surface waters by the diffusion of animal waste into the environment is well documented (Khaleel et al., 1980; Crane et al., 1983; Baxter-Potter & Gilliland, 1988). The following discussion addresses the duality of animal waste as both an asset and a pollutant, management methods used to deal with the ever-increasing volumes of animal waste, and finally, methods used by investigators to evaluate the impacts of animal waste best management practices (BMPs) on surface water quality.

Animal Waste

The term "animal waste" includes both the feces and urine wastes of livestock and poultry, as well as any process water, feed, bedding, litter, or soil which can become intermingled with such materials. Animal waste contains sediment, organic solids, nutrients, salts, oxygen-depleting substances, and microorganisms including bacteria, viruses, and others (USEPA, 1993). Animal wastes are capable of being both an asset as well as a potential liability to land operators.

There are a variety of uses for animal wastes including as a fuel source, animal bedding, animal feed, mulch, organic matter, and plant nutrients (Safley et al., 1992). Land application of animal wastes is a common method of utilization. Depending on the water content of the material, animal wastes are placed in one of four categories—solid, semi-solid, slurry, or liquid. Water content of animal waste dictates the farmer's options for handling the material. However, if one method is preferred over another, the farmer can alter the consistency of the waste by adding either bedding material (to increase the solids content) or water (to decrease the solids content) (MWPS, 1993). Typically, wastes are land applied in one of four manners: knifed, irrigated, broadcast with plowdown or disking, or broadcast without plowdown or disking,.

The incorporation of animal waste into the soil profile can be met with multiple benefits. Improvements in soil tilth, water holding capacity, and aeration are all reported advantages of manure addition to the soil (MWPS, 1993). Also, land-applied manure can increase soil resistance to both wind and water erosion (MWPS, 1993). Organic material contained within the waste can improve soil structure as well as the soil's infiltration capacity (USDA, 1992). Enhanced fertility of the receiving soils is credited to the nutrients present in the animal waste material (MWPS, 1993). As the animal wastes are degraded by indigenous microorganisms, nutrients are slowly released. This slow release conserves the nutrients and allows them to be available to the crop throughout the growing season. However, since the rate of such releases is uncontrollable, this can be viewed as a disadvantage as well (USDA, 1992). Finally, the economic value of manure can be determined by its nutrient content (N, P, and K) and the material can be sold as commercial fertilizer (USDA, 1992). Table 2.1 gives some typical values for nutrient content in various farm animal manure.

Table 2.1. Nutrients in fresh livestock manure (MWPS, 1992)

Animal	Size (kg)	N (kg/yr)	P_2O_5 (kg/yr)	K_2O (kg/yr)
Dairy cattle	68	10	5	8
	113	18	7	15
	227	35	15	28
	454	70	28	56
	635	98	40	79
Beef cattle	227	28	21	25
	340	43	31	36
	454	56	41	50
	567	71	51	63
Swine				
Nursery pig	16	3	2	2
Growing pig	29	5	4	4
Finishing pig	68	12	8	9
	91	15	11	12
Gestating sow	125	12	8	8
Sow and liter	170	17	9	9
Boar	159	15	10	10
Sheep	45	7	3	6
Poultry				
Layers	2	0	0	0
Broilers	1	0	0	0
Horse	454	50	27	50

An integral component of any livestock operation is an adequate waste management plan. A well-planned and well-executed agricultural waste management system (AWMS) should sustain or enhance the quality of air, water, soil, plant and animal resources. Safley et al. (1992) identify six functions of a properly designed and functioning AWMS: production, collection, storage, treatment, transfer, and utilization. These functions may be combined, repeated, eliminated, and/or arranged as appropriate for each site-specific system.

Animal Waste Impacts on Water Quality

Despite the many benefits which can result from manure addition to the soil, the diffusion of animal waste into the environment can cause severe natural resource degradation (Walter et al., 1992). According to the USDA (1992), the components of manure which have the most adverse impact upon surface waters are organic matter, nutrients, and fecal bacteria. Oxygen is required for the microbial degradation of organic mater in surface waters receiving runoff containing animal waste. Thus, the more organic mater which is conveyed to the surface waters, the greater the oxygen demand will be in order for breakdown to occur. Therefore, less dissolved oxygen will be available for the indigenous aquatic species. Increased levels of nutrients lead to eutrophication of the receiving waters as well as algal blooms. The USEPA (1976) suggests that levels of nitrogen and phosphorus be maintained below 0.30mg/L and 0.01mg/L, respectively, in order to prevent eutrophic growth. Additionally, the presence of ammonia in surface waters is toxic to fish. The microbial content of manure can lend itself to potential human and animal health problems.

Numerous studies have been conducted which document the adverse affects of animal waste contributions to nonpoint source pollution from various agricultural activities (Younos et al., 1997; Khaleel et al., 1980; Edwards et al., 1997a; Edwards et al., 1997b; Patni et al., 1985). Ten month pre-BMP monitoring data of a dairy loafing lot concluded that animal waste present in storm water runoff severely impacted the receiving stream water quality (Younos et al., 1997). Decreases in water quality have been related to the presence of livestock. The presence of cattle near a water receiving runoff from storm events has been proven to decrease water quality (Howell et al., 1995; Fernandez-Alvarez et al., 1991; Gary et al., 1983). From the chemical and bacteriological monitoring data of pasture land, Doran et al. (1981) concluded that cattle grazing was influential in the water quality of the proximal streams, although they reported vegetative cover and wildlife activities were also prominent factors. Thus, the relationship between agriculture and fecal bacteria in streams draining complex watersheds is poorly understood (Meals, 1989).

Animal Waste Pathogens

There are primarily eight causative pathogenic microorganisms—bacteria toxins, bacteria, spirochetes, viruses, rickettsia, protozoa, helminths, and fungi (Sterritt & Lester, 1988). Not all are included in animal manure, as is demonstrated in Table 2.2.

The quantity of microbes associated with animal manure is a function of both the number and type of contributing livestock (Khaleel et al., 1980). Clearly, the more animals present, the greater the possibility of fecal microorganisms. Table 2.3 demonstrates the variation of bacterial quantity among numerous animal types.

Table 2.2. Diseases and organisms spread by animal manure (Walter et al., 1992)

Responsible organism	Disease	Responsible organism	Disease	Responsible organism	Disease
Bacterial		**Rickettsial**		**Protozoal**	
Salmonella sp.	Salmonella	*Coxiella burenti*	Q fever	*Eimeria sp*	Coccidiosis
Leptospiral pomona	Leptospirosis	Viral		*Balatidium coli*	Balatidiasis
Bacillus anthracis	Anthrax	Virus	Hog Cholera	*Toxoplasma sp*	Toxoplasmosis
Mycobacterim tuberculosis	Tuberculosis	Virus	Foot and Mouth	**Parasitic**	
Brucella abortus	Brucellosis	Virus	Psittacosis	Ascaris lumbricoides	Ascariasis
Clostridium tetani	Tetanus	**Fungal**		Sarcocystis sp.	Sarcocystiasis
Pasturella tularensis	Tularemia	*Coccidoides immitus*	Coccidioidomycosis		
		Histoplasma capsulatum	Histoplasmosis		
		Various microsporum and trichophyton	Ringworm		

Pathogen survival

Since the land-application of animal wastes is a major source of pathogens, it is therefore a potential health hazard for both humans and animals (Crane et al., 1980; Abu-Ashour et al., 1994). The presence and survival of pathogens in such situations, however, is poorly understood, as it is confounded by many factors such as soil characteristics, manure application rates, timing, duration, and intensity of runoff events, and proximity of receiving waters (Crane et al., 1983; Baxter-Potter & Gilliand, 1988). Microbial survival is influenced by a variety of biotic and abiotic conditions. Factors which affect bacterial survival in a soil environment include pH, temperature, moisture and nutrient availability, solar radiation, competition, predation and exposure to toxic compounds (Gaudy & Gaudy, 1980; Ellis & McCalla, 1978).

Table 2.3. Microbial Densities Among Various Animals (Geldreich, 1978)

Animal	Fecal Coliform density per gram of feces	Fecal Streptococcus density per gram of feces
Cow	230,000	1,300,000
Chicken	1,300,000	3,400,000
Chipmunk	148,000	6,000,000
Duck	33,000,000	54,000,000
Horse	12,600	6,300,000
Pig	3,300,000	84,000,000
Rabbit	20	47,000
Sheep	16,000,000	38,000,000
Turkey	290,000	2,800,000
Human	13,000,000	3,000,000

A first-order decay equation is commonly used to approximate microbial die-off (Mitchell & Chamberlin, 1978). The most common die-off model follows the expression of Chick's Law (Mitchell & Chamberlin, 1978):

$$\frac{dC}{dt} = -kC \qquad (2.1)$$

where C = concentration of coliform bacteria

k = over-all decay or die-off rate

t = time coordinate

The value for k is dependent upon temperature and can be found in the literature (Mancini, 1978). Crane et al. (1980) used such mathematical techniques to describe microbial survival in soils amended with poultry manure. They reported such models described an incomplete model of microbial survival, as fecal streptococci die-off was not accurately estimated, nor did the model account for regrowth of fecal bacteria which could occur. First-order decay, however, continues to be the most common model used to describe the phenomena of microbial die-off.

An additional consideration when investigating microbial survival in land applied manure is the natural filtering action provided by the soil column, as well as die-off and predation of the microorganisms by indigenous soil biota (Brock & Madigan, 1989). As agricultural runoff that is washed offsite begins to percolate into the soil, the soil acts as a natural filter to trap the microbes and prevent further movement through the soil column (Crane et al., 1980; Ellis & McCalla, 1978). However, if the pore size of the soil is large enough, or the microbe is small enough (i.e.

viruses) so as to permit passage through the soil column, then the risk of groundwater contamination is increased. Once fecal microorganisms are removed from their ecological niche of warm-blooded intestines, the changes in environmental conditions are drastic enough to induce die-off, thus reducing movement through the soil and possible risk of groundwater contamination. Finally, the upper soil profile maintains such a high level of biological activity that a non-indigenous microbe would be subject to such intense competition and extensive predation that its chances of percolating through the soil and reaching groundwater are again diminished. However, research on soil temperature has concluded that fecal bacteria viability is increased as soil temperatures drop (Faust, 1982).

Since a large percentage of pathogens associated with animal waste are retained close to the soil surface, the potential for runoff is significant (Khaleel et al., 1980). The presence of microorganisms in overland flow is dependent on several factors. Rainfall intensity and duration, the method of manure application, the age of the fecal material, and the adsorption of the cells to soil particles are all important considerations when evaluating bacterial presence in stormflow. Springer et al. (1983) hypothesized that higher intensity storms cause more erosion and overland flow and thus more microbial transport. The transport of microorganisms was found to have a direct correlation with rainfall duration (Springer et al., 1983). Other studies (Moore et al., 1988) determined that solid land applied manure has greater movement of organisms via overland flow than manure applied as a liquid. Furthermore, Moore et al. (1988) determined that the amount of microorganisms associated with manure is inversely proportional to the age of the waste material. The literature identifies several influential factors surrounding microbial transport in storm water flow, and suggests that information concerning this process is incomplete and poorly understood.

Indicator organisms

The ingestion of fecally contaminated water could result in major health complications for both humans and animals. In order to circumvent such occurrences, it became necessary to devise analytical tests capable of determining the presence of such disease-causing organisms as *Vibrio cholerae* (responsible for Cholera), *Shigella dysenteriae* (Bacterial dysentery), and *Giardia lamblia* (Giardiasis). However, the ability to test a water sample for the presence of every human pathogen would be excessively time-consuming and economically impractical. Thus arose the notion of indicator organisms (Gaudy & Gaudy, 1980).

The concept behind the use of indicator organisms is quite simple. An indicator organism is a nonpathogenic microbe which is present in fecal material and is relatively easy to detect in a water sample (Thelin & Gifford, 1983; Gaudy & Gaudy, 1980). The presence of an indicator organism is indicative of fecal contamination of the water, but not necessarily the presence of pathogens. The quality of water is then determined by testing the presence, absence, and/or abundance of this "indicator" organism. The indicator organism thus acts as an alarm to alert of fecal contamination and to suggest that potential water quality problems could, but not necessarily, exist. Organisms commonly used as indicators include total coliforms (TC), fecal coliforms (FC) and fecal streptococci (FS) (Gaudy & Gaudy, 1980). The APHA (1992) provides several acceptable methods for determining the quality of a water sample using these indicators.

Coliform bacteria are included in the Enterobacteriaceae family (Sterritt & Lester, 1988). Bacteria within this family are gram negative, non-sporeforming, rod-shaped, facultative anaerobes. Additionally, these bacteria ferment lactose with gas and acid production within 48 hours at 35^0 C. Fecal coliform bacteria are distinguished by their ability to ferment lactose with acid and gas production within 24 hours at 44^0 C. Fecal streptococci are members of the Streptococcaceae family, defined as gram negative, cocci shaped, facultative anaerobes (Sterritt & Lester, 1988).

There is much debate as to which group serves as the best indicator organism as all three possess both strengths and weaknesses. Total coliform bacteria are useful in situations where any bacterial presence is undesirable. These bacteria, however, include species which are non-enteric and have a tendency to reproduce in high nutrient waters, thus overestimating the extent of fecal contamination. Fecal coliform bacteria are highly correlated with fecal contamination, yet are not always accurate in predictions of water contamination. Fecal streptococcus bacteria also have a high correlation with fecal contamination, although they often have a quicker die-off rate than some pathogens, producing misleading results. Faust (1982) found fecal coliform bacteria to be the best indicator of recent fecal contamination of surface waters. The legislation varies from state to state as to which organism is used as the basis of water quality standards. Crane et al. (1983) suggest that the choice of the most appropriate indicator organism must consider both the purpose of the data collection and the surrounding conditions of the sample source.

Monitoring

Monitoring is a tool which enables investigators to directly evaluate the quality of water in response to changes in management practices (USEPA, 1993). Since monitoring is often one component of larger program efforts, specific monitoring objectives are typically defined for each project. Seven types of monitoring are described by MacDonald (1991) including:

(1) Baseline monitoring;
(2) Compliance monitoring;
(3) Effectiveness monitoring;
(4) Implementation monitoring;
(5) Project monitoring;
(6) Trend monitoring; and
(7) Validation monitoring

Such techniques are useful for identifying critical areas and for prioritization of federal or cost-share money allocation for improvements. It is not uncommon for monitoring projects to include more than one type of monitoring.

Proper design of a monitoring program is fundamental, as it provides the framework for data collection, analysis, and interpretation (Coffey & Smolen, 1990). When developing a monitoring system which is to provide information on watershed trend detection, Meals (1991) reports five major components to include:

(1) Understand the system to be monitored;
(2) consider the objectives when designing the monitoring system;
(3) be attentive to details from the beginning;
(4) monitor source activities; and
(5) build in feedback loops.

The diffuse nature of agricultural runoff often leads to difficulties when designing control measures. As a means to document water quality improvements derived from NPS control measures, Spooner et al. (1985) describe three types of experimental designs: time trend analyses, above and below analyses, and a paired watershed design. If monitoring of a site occurs over an extended period, time trend analysis allows the investigator to observe changes in water quality. Chandler and Maret (1992) report that unless other variables are measured which can relate improvements in water quality to changes in land use, the time trend analysis method has low sensitivity. The upstream-downstream technique is useful if one wants to investigate the upstream impacts on water quality. The paired watershed approach provides for the monitoring of two or more agricultural basins where at least one drainage basin has BMP implementation while one basin is left untreated as a control. This method is very useful in accounting for variability due to meteorological factors as well as providing statistically strong evidence for a direct correlation between agronomic practices and water quality improvements (Chandler & Maret, 1992).

Animal Waste Impacts on Water Quality

For nearly three decades, a heightened awareness has surrounded the issue of nonpoint source pollution. Monitoring has aided researchers in their attempt to understand the driving forces and complex processes involved in NPS pollution. Animal waste management methods have been adopted, both voluntarily and otherwise, with the hopes of improving water bodies susceptible to agricultural storm water runoff.

Because animal waste materials include numerous potential pollutants, the design of BMPs to counter the effects of such contaminants cannot be based solely on one component (i.e. fecal bacteria, nutrients, suspended solids, etc.). Thus, animal waste management methods have been developed with the intention of reducing the losses of multiple pollutants commonly associated with animal waste.

Animal Waste Storage Structures

A variety of benefits can be derived from implementing animal waste storage units. Storage of animal waste yields pathogen die-off by providing a hostile environment for the microbes (Crane et al., 1983; Thelin & Gifford, 1983). As previously noted, microorganisms have a defined range of various abiotic conditions including temperature, pH, and oxygen and moisture requirements, which must be present in order to remain viable. Storage of animal waste denies microorganisms access to these necessary conditions, resulting in die-off. Facilities for the containment and storage of animal wastes can be either concrete or earthen structures. The American Society of Agricultural Engineers (ASAE) has published standards (1993) detailing criteria for the design and construction of this management option.

An additional benefit credited to manure storage is that storage allows for proper climatic conditions for land application of the wastes. Ideally, manure should be land-applied 24 to 72 hours prior to a rainfall event (Crane et al., 1983; Crane et al., 1980). However, this necessitates an accurate weather prediction, which is not always feasible. Manure application at least 24 hours before a rain event allows for soil incorporation of the waste material, reducing the amount of manure susceptible to erosion and overland flow (Crane et al., 1983). Manure should not be spread on frozen ground, as lower soil temperatures have been proven to increase the survival of fecal bacteria (Crane et al., 1983; Faust, 1982). It is best to have vegetation on the land in order to uptake the nutrients contained within the manure. Thus by storing the waste material, land operators are allowed more flexibility in terms of when land application will occur. Using computer simulation, Walker et al. (1990) found using storage to manage animal wastes an effective means by which to improve the bacteriological quality of receiving streams. Similar results were found by Moore et al. (1988). In a watershed study of BMPs, Meals (1992) found that animal waste storage significantly lowered the fecal bacteria levels in streams receiving runoff from manure-applied lands. Patni et al. (1985) reported fecal coliform and fecal streptococcus bacteria die-off of near 99% when storing animal wastes prior to land application.

Ambient soil surface temperatures can greatly affect the amount of pathogens available to become part of overland flow. Cooler temperatures can increase pathogen survival time by slowing down metabolic activity thereby increasing microbial survival time and the potential for microbial presence in storm runoff (Khaleel et al., 1980; Crane et al., 1983; Faust, 1982). Thus, the purpose of animal waste storage is two-fold—to promote pathogen die-off and to encourage properly-timed land applications.

Manure Incorporation

Proper incorporation of land-applied wastes into the soil profile eliminates the potential for pollutants to be transported off-site via overland flow (Crane et al., 1983; Eghball & Power, 1994). It follows that any microbial content associated with the waste would also remain within the soil, rather than being conveyed with the soil particle via the runoff. Thus, the potential for microbial contamination of receiving waters would be greatly reduced. Soil incorporation of animal wastes has additional benefits as well, including decreased odor and fly problems, reduced unsightly appearances, reduced volatilization, and increased crop nutrient use (Eghball & Power, 1994). The physical properties of the soil including infiltration, aggregation and bulk density can also be improved via manure incorporation (Eghball & Power, 1994). These soil properties will then have a direct impact upon the infiltrative capacity of the soil profile and thus the runoff potential. Walker et al. (1990) found that incorporation of manure into the soil profile was an effective means by which to reduce fecal bacteria in overland flow. Giddens and Barnett (1980) studied the effects of poultry litter incorporation into the soil profile and found reductions in the microbial presence in runoff. Similar results have been reported by other investigators (Moore et al. 1988; Crane et al., 1983)) Therefore, the incorporation of animal wastes into the soil improves soil characteristics and reduces the potential for NPS pollution.

Vegetative filter strips

Vegetative filter strips (VFS) are defined as "bands of planted or indigenous vegetation situated between pollutant source areas and receiving waters that are intended to remove sediment and other pollutants from surface runoff and to enhance wildlife habitat values" (Dillaha et al., 1988). VFS are not intended to reduce the amount of generated pollution, rather to separate the pollutants from the runoff, and are therefore considered a structural management practice.

Buffer length is a primary consideration when utilizing VFS (Crane et al., 1983; Khaleel et al., 1980; Chaubey et al., 1994). The length determines the amount of contact time the runoff (and therefore pollutants conveyed within the runoff) will have with the VFS. Also important when designing a VFS is the vegetative type, topography of the proposed site, and the potential rainfall intensity and storm volume (Crane et al., 1983).

Extensive research has been conducted in the area of vegetative filter strips (Dillaha et al., 1985, 1986, 1987, 1988, 1989; Magette et al., 1986, 1987, 1989), however, the literature suggests that the use of VFS to filter out microorganisms in diffuse pollution has been met with mixed results. Jenkins et al. (1978) found VFS effective in removing 96 to 99 % of the fecal coliform bacteria content during the summer season. Young et al. (1980) used a rainfall simulator to study various NPS pollutants in feedlot runoff for two years. They found fecal coliform levels to be reduced nearly 70% once the flow was conveyed through the filter strip. However, both Coyne et al. (1995) and Walker et al. (1990) concurred that the use of VFS alone does not significantly affect the microbial concentration of overland flow. In a study by Chaubey et al. (1994), filters strips of fescue significantly reduced the transport of various nutrients (ammonia nitrogen, NH_3-N; total Kjeldahl nitrogen, TKN; ortho-phosphorus, PO_4-P; and total phosphorus, TP) and suspended solids, however, the reductions in fecal bacteria were small. Thus, consistent results concerning microbial removal from overland flow by VFS have not yet been attained.

Statistical Methods

Water quality data, including biological data, have often been regarded as difficult to analyze because the data sets typically fail to have a normal distribution, are bound by zero, and/or are often below instrument detection limits (Walter, 1994). If a water quality data set can be transformed in some sort of manner (i.e. logarithmically, inversely, etc.) to then follow a normal distribution, the application of parametric statistical tests would be acceptable. Nonparametric statistical techniques, in contrast, have no such distribution restrictions, and are therefore often employed in the analysis of water pollution data. Researchers have reported use of both types of data analysis techniques when evaluating water quality data.

Edwards et al. (1997b) collected nearly 3 years of bacteriological data from 4 field sampling locations in northwest Arkansas. The objective of this research was to evaluate the impact of grazing, season, and runoff levels on fecal coliform and fecal streptococci levels. Two of the fields were treated with ammonium nitrate (NH_4NO_2) inorganic fertilizer while the other two were amended with poultry manure and poultry litter. Runoff events were measured and samples were collected as soon as possible following the event. Samples were analyzed according to APHA standards (APHA, 1992). To evaluate the effects of grazing, bacteriological samples were grouped according to whether or not the cattle were present during the runoff event. Once this distinction was made, the standard T-test comparing the means of the natural logarithms of the runoff concentration was used. The presence or absence of cattle was not found to contribute significantly to the levels of indicator bacteria. The impact of season was evaluated by dividing the data into four seasons and conducting a one-way analysis of variance (ANOVA) on the natural logs of the bacteria. Seasons were found to have a significant effect on the bacterial concentrations, with the greatest levels being observed during the warmer months. A regression of flow-weighted bacteria concentrations against runoff was performed, but no significant effect was found.

In a separate study, Edwards et al. (1997a) evaluated FC and FS levels along with season and flow rates in hopes of determining the impact of these factors on the bacteria quality of runoff. Approximately three years of FC and FS monitoring was conducted at five sites located within two northwest Arkansas streams. Two of the sites recorded flow data. The predominant landuse in the area was pasture and forest. The natural logarithm of the bacteria was regressed against the natural log of the flow rate. In most cases, flow rate was found to have a significant influence on bacteria levels. The FC and FS data were divided into four seasons and the natural logs were analyzed using a one-way ANOVA. The studentized Neuman-Keuls test was then used to separate seasonal means identified as significant by the ANOVA. Season was consistently reported to be significant at all sampling sites, with highest impacts during the summer.

Farrell-Poe et al. (1997) studied the bacterial contributions to nonpoint source pollution of four rural municipalities in Utah. Monitoring sites were established upstream and downstream of each municipality while grab samples were taken bimonthly during the winter months and on a weekly frequency otherwise. Continuous sampling occurred for 15 months. Parametric statistical analysis was used to determine mean concentrations of total and fecal coliform bacteria. The Kruskall-Wallis nonparametric test was used to observe differences between upstream and downstream data from each municipality. Significant differences were found among all municipalities. Fisher's pairwise test was employed to determine if municipalities contributed significantly different amounts of either bacteria in the runoff samples. Significant differences were found in all cases. Finally, using Spearman's-rho (Conover, 1980), no correlation was found between bacteria concentration and flow.

A comparison of the bacteriological quality of runoff from cropland receiving manure to that of unmanured cropland was made by Patni et al. (1985). A total of seven stations were monitored, and non-snow melt runoff grab samples were collected, flow permitting, for three years, generally with a one- to three-times per week frequency. Samples were analyzed for TC, FC and FS. A one-way ANOVA was applied to the log-transformed bacteria data, and a significant difference from year to year and station to station was found for all three bacteria parameters. The student's t-test was used to compare the yearly mean of selected stations with other stations. In general, a significant difference was not found, thus suggesting that the bacterial quality in runoff from manured land was not significantly difference from that of land which did not receive manure applications.

The presence of fecal bacteria in runoff from agricultural areas is well documented, although the processes involved in the survival and movement of this pollutant through the environment are complex and not completely understood. Conflicting results from the investigations of the common management methods used to control fecal pollution of nearby streams have provided further support for the complexity and incomplete understanding of these natural phenomena. Little research has been done to document the watershed response to a combination of BMPs and the resulting impact on the bacteriological quality of surface waters.

Methodology

Site Description

In order to determine both short term and long term effects of animal waste management practices on stream water quality, the Owl Run watershed (Figure 3.1) was selected as the focus of a 10-year monitoring project in 1986. The Owl Run watershed occupies 1163 ha within Fauquier County, Virginia, which is located approximately 65 km southwest of the Nation's capital. The primary landuse within this drainage basin is agriculture, as the land area supports 5 major dairy operations. This watershed was selected for the study based on its extensive agricultural use of the land and the apparent lack of animal waste management practices at the initiation of the project (Mostaghimi et al., 1989).

Fauquier County is situated in both the Piedmont and Blue Ridge Mountains physiographic regions of Virginia. Approximately 80% of the county is comprised of the Piedmont Plateau, while the Blue Ridge Mountains occupy the northwestern part of the county.

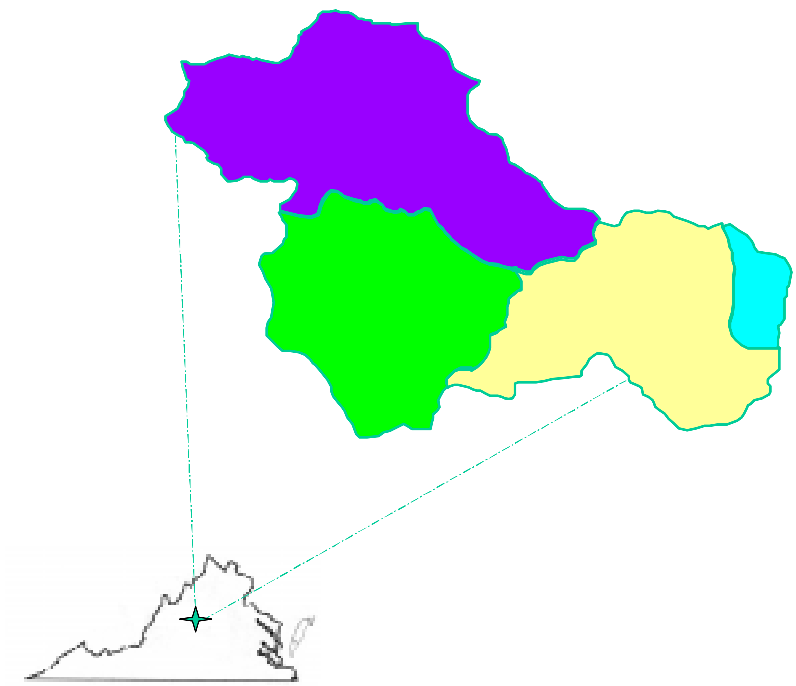


Figure 3.1 Location of the Owl Run watershed

The greater part of the county's terrain is steep and rugged. This part of the U.S. experiences a humid, continental type climate, with typically hot, humid summers and relatively mild winters. Average annual rainfall is approximately 104 cm, the majority of which occurs during the spring and is fairly well distributed throughout the county (Mostaghimi et al., 1989).

Soils

Soils within the watershed are mostly shallow (0.3-0.6 m) silt loams, overlying Triassic shale. Approximately 72% of the soil series within the watershed is made up of the Penn (40%), Bucks (16%) and Montalto (16%) associations (SCS, 1956). Information on specific soil types is included in Table 3.1. The Penn soils are derived from Triassic Red shale and sandstone—specifically, the silt loam from the shale and the loam from the sandstone. These soils are shallow and excessively drained, occurring mainly in undulating to rolling relief. The color of the surface soil varies from reddish brown with a purplish cast, to dark reddish brown. The Penn associations typically have medium runoff and medium to rapid internal drainage. Soil permeability is moderate while the water holding capacity is poor. The Bucks soil series, developed over Triassic red shale and sandstone, are moderately deep, well-drained upland soils. The surface soil is brown in color with a dark reddish brown subsoil. The Bucks typically occupy moderately large areas on broad, undulating ridges which join the Penn soils. The Bucks soils have slow to medium runoff with medium internal drainage. The soils within the Bucks association are strongly to very strongly acidic and carry a fairly high organic matter content. The Montalto soils, developed over fine grained Triassic diabase, are moderately shallow, well-drained soils. These soils are typically reddish brown in color with medium runoff and internal drainage. Montalto soils are relatively fertile, due to the good supply of organic matter and plant nutrients. They are medium to strongly acidic and because of their dark color and shallowness, the soils warm and dry sufficiently in the spring to permit early plowing (SCS, 1956).

Table 3.1. Soil Types in the Owl Run Watershed (Mostaghimi et al., 1989)

Soil Type	Percent Slope	Area of Watershed (ha)	Percent of Watershed
Bowman silt loam	0-2	14	1.2
Bucks silt loam, undulating phase	2-7	188	16.3
Calverton, undulating phase	2-7	95	8.2
Croton silt loam	0-5	101	8.8
Kelley silt loam, level and undulating phase	2-7	28	2.4
Montalto silt loam, undulating moderately shallow phase	2-7	17	14.4
Montalto stony silt loam, rolling moderately shallow phase	7-14	23	2.0
Penn silt loam, undulating phase	2-7	412	35.7
Penn silt loam, rolling phase	7-14	47	4.1
Rowland silt loam	0-2	33	2.9
Wadesboro silt loam, undulating phase	2-7	16	1.4
Other	0-25	30	2.6

Landuse

Nearly 70% of the Owl Run watershed is used in agricultural production, including both cropping and livestock productions. The remainder of the watershed includes residential, commercial, transportation and forested areas. Table 3.2 provides a more detailed breakdown of the landuse within the watershed. 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 a grass legume hay, seeded with a small grain companion crop (Mostaghimi et al., 1989). The watershed supports 5 major dairies, one replacement heifer operation, and three small cattle operations. When the project was first initiated, only one of the five dairies was employing any type of waste management practice. Since then, the landuse and agronomic practices have been evaluated and altered, with the anticipation of improved water quality.

Table 3.2. Typical Landuse Activities in the Owl Run Watershed (Mostaghimi et al., 1989)

Land Use Category	Area of Watershed (ha)	Percentage of Watershed Area
Corn (conventional till)	173	15
Corn (no-till)	127	11
Rotational hay	231	20
Pasture (active)	208	18
Pasture (idle)	81	7
Woodland	231	20
Non-agricultural	104	9

Accurate compilation of the land activity data throughout the duration of the monitoring was essential if the overall goal of the project was to be realized. Thus, a geographic information system (GIS) database was created in order to manage the ten years of land use data. Five layers were digitized and stored in raster format. The data layers, with a 1/9 ha resolution, included watershed boundaries, stream elevations, soil types, and general land use. Linked to the field boundaries within the GIS database was another database which detailed the allocation and usage of the land during two periods within each year. Landuse activities were collected twice per year, consequently "LU1" refers to the landuse data from April through October and "LU2" is the reported landuse from November through March. The landuse activities in the watershed were documented throughout the project lifespan. Annual average landuse areas throughout the monitoring project are included in Table 3.3. Note that both cropland and pasture had noticeable increases in area from the pre- to the post-BMP period, 11% and 27%, respectively.

Table 3.3 Summary of Owl Run Landuse

	Landuse Area (hectares)							
	Farmstead	Cropland	Nonag	Forest	Pasture	Inactive ag land	Other *	Total
1986	25.2	336.2	117.0	307.7	215.8	71.4	89.7	1163.0
1987	25.2	325.4	117.0	306.7	199.4	71.4	117.8	1163.0
1988	25.2	397.8	117.1	306.7	211.6	13.8	90.7	1163.0
1989	25.2	343.7	117.1	304.3	218.0	29.9	124.6	1163.0
1990	25.2	394.1	117.1	304.3	228.8	35.0	58.4	1163.0
1991	20.0	381.9	111.6	309.3	263.2	68.0	9.1	1163.0
1992	20.0	368.0	111.6	309.2	264.4	80.8	9.1	1163.0
1993	20.0	429.4	110.6	304.9	275.8	13.9	8.2	1162.9
1994	20.0	410.3	114.2	305.2	291.0	14.2	8.0	1163.0
1995	20.0	410.3	114.2	305.2	289.9	15.5	8.0	1163.0
1996	20.0	410.3	114.1	305.2	289.9	15.5	8.0	1163.0
Pre-BMP average	25.2	356.4	117.1	306.5	209.3	44.6	103.9	1163.0
Post-BMP average	21.1	395.0	113.6	306.1	266.7	36.0	24.5	1163.0

* Other includes ponds, ‘no report’, grassed waterways, and crp land, as typically these landuse categories were less than 5% of the watershed area.

Information detailing landuse was stored and analyzed using the PC-VirGIS (MapTech, 1995) geographic information systems computer software. The landuse data were then used to show the changes which occurred as a result of the adoption of various management practices in conjunction with the monitoring project. The water quality data were compared to the landuse records in order to relate changes in water quality to the landuse practices implemented in the watershed.

Animals

Five major dairy and several beef operations were functional within the Owl Run watershed during the monitoring project. Table 3.4 provides information on the number and type of livestock present in the watershed for both the pre- and post-BMP periods. Livestock numbers increased by 2% from the pre- to the post-BMP period. This increase occurred only in the dairy operations, as the beef operations experienced a decline in numbers over the course of the investigation.

Table 3.4 Owl Run Livestock Operations

Farm Name	Type	Animal Numbers		Comments
		Pre-BMP	Post-BMP	
Hi Hope	Dairy	475	475	
Eastern View	Dairy	145	175	3/yr increase
Day Bros (Mayhugh)	Dairy	120	120	
P. Law (Bender)	Dairy	65	65	
J. Cassell	Dairy	135	155	2/yr increase
Gray	Dairy	60	60	Mostly replacement heifers
Riddell	Beef	50	50	
	Horses	4	4	
Armstrong	Beef	30		Usage has declined
Ely	Beef	60	60	
Total		1144	1164	

Confinement of the dairy cattle was virtually 100% during the months of December, January and February, which indicates more manure management required during these months. Six hours of confinement was typical during the remaining months, although inclement weather during the early spring and late autumn could increase this time. At the initiation of the watershed monitoring, only the Cassell dairy facility had animal waste storage associated with the operation. Prior to the installation of the waste storage tanks in conjunction with the investigation, farm operators land-applied the material on a daily or weekly frequency. Five waste storage structures were designed and installed as a part of this study. Table 3.5 tabulates the size and cost of these structures. The locations of the various waste structures in the watershed are identified in Figure 3.2

Table 3.5. Animal waste storage structure information

Farm Name	Date Installed	Waste storage structure capacity (m^3)	Cost ($)
Hi-Hope (dairy)	1/2/90	2,063	106,030.94
Hi-Hope (hog)	6/5/89	72	15,471.00
Eastern View	6/7/88	1,423	85,544.00
J. Cassell	9/14/88	1,469	115,554.25
Pete Laws	12/13/88	1,381	19,137.52

Typically, the waste structures were designed to hold six months of material. Site restrictions, such as plot size, limited the design and capacity of the storage facility. The previously operating waste storage structure located on the Cassell property was approximately 850 cubic meters in size and provided roughly 2 to 2 ½ months storage of the material. It is a concrete structure and was constructed in the early 1980's. All five of the animal waste storage structures built in conjunction with the monitoring project were designed by personnel at the Department of Conservation and Recreation. Construction of the facilities occurred over a two-year period beginning in the summer of 1988 and finishing at the beginning of 1990.

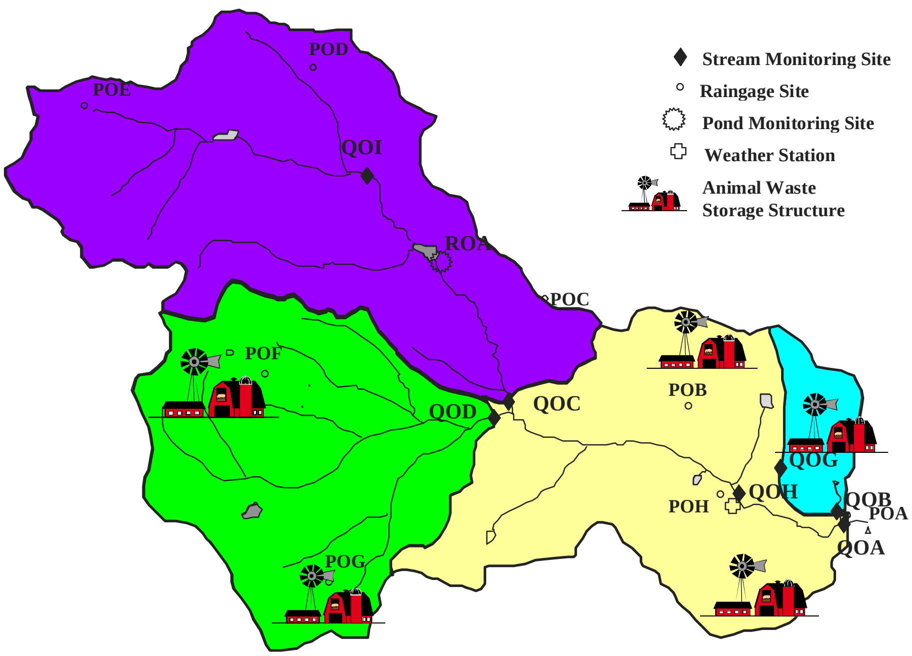


Figure 3.2. Location of monitoring stations and waste storage structures (Mostaghimi et al., 1997)

Nutrient/Fertilizer Application

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 & 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 NPS pollution. Specifically, implementation of this management practice contributes to increased microbial die-off by providing a hostile environment for the fecal microbes, and allows for more opportune climatic and agronomic conditions for the fields receiving such manure applications. The selection of fields to receive waste applications prior to the implementation of the waste storage facilities was based primarily on proximity during the pre-BMP period. 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 the material to fields where the material could be best utilized, rather than those fields most readily accessed.

The collection of detailed records of fields receiving manure application and the amount of nutrients applied began during the post-BMP period and were therefore approximated for the pre-BMP period. After the installation of the animal waste storage facilities, the frequency of manure application to fields was reduced drastically. Because the storage facilities were typically designed to accommodate six months of waste material, land application of animal waste was reduced to twice per year during the post-BMP monitoring period, once in the spring and once in the autumn. Some daily hauling of the material still occurred, primarily at the Day Dairy and occasionally at the Hi Hope operation (Pane, 1997). Weather was very influential in deciding the precise time period of disposal, however a generalized schedule of manure application once the storage facilities were operational is presented in Table 3.6.

Table 3.6 Typical manure application schedule in the Owl Run watershed

Time of Application	Date	Percent of stored waste spread
Spring	March 26—April 1	5
	April 1—April 8	10
	April 8—April 22	50
	April 22—April 29	25
	April 29—May 6	10
Autumn	August 27—September 6	10
	September 6—September 13	10
	September 13—September 27	50
	September 27—October 4	15
	October 4—October 21	15

Nutrient management plans were developed for each of the dairy operations by the personnel at the Department of Conservation and Recreation. Technical support for the land-operators concerning these management methods was available through the USDA SCS office. Records of fertilizer applications, both synthetic and manure, were recorded twice per year. Table 3.7 presents the annual fertilizer application amounts for the entire watershed, highlighting the manure nutrient contributions. Note that the manure nutrients for both 1987 and 1988 were approximated.

Table 3.7a. Annual nutrient applications on agricultural land within the Owl Run watershed

Year	Annual Manure Application Rate m^3/ha	Nitrogen Rate Kg/ha *	Nitrogen Manure Nutrients Kg/ha *	Nitrogen % manure nutrients**	Phosphorus Rate Kg/ha *	Phosphorus Manure Nutrients Kg/ha *	Phosphorus % manure nutrients **	Potassium Rate Kg/ha *	Potassium Manure Nutrients Kg/ha *	Potassium % manure nutrients
1987	47	131	31	24	38	65	170	83	92	111
1988	38	118	25	22	57	53	94	89	75	85
1989	28	148	31	21	78	41	53	127	71	56
1990	20	128	21	16	56	25	45	91	39	43
1991	21	99	18	18	46	27	59	76	41	54
1992	26	117	18	15	66	25	38	121	49	40
1993	21	93	20	21	59	24	41	99	47	48
1994	27	129	24	18	73	34	47	84	58	68
1995	15	108	37	34	70	41	59	110	71	64
Pre-BMP Average	38	132	29	22	58	53	106	100	80	84
Post-BMP Average	22	112	23	21	62	29	48	97	51	53

* rate is calculated based on cropland area
** % manure nutrients = manure nutrients / nutrient rate * 100

Throughout the Owl Run watershed, the ‘cropland’ designation accounted for approximately 35% of the overall landuse. Typically, it was these areas which received the majority of the land-applied wastes. Pasture land, which comprised roughly 25% of the watershed, also received a portion of the waste, both from the farmer’s land application, as well as directly from the grazing cattle. The rate of nutrient application to the land was dependent upon the crop need as well as the amount of waste which required disposal. As Table 3.7a shows, the annual manure application rate decreased notably from the pre- to the post-BMP period, as did the amount of:

nitrogen (both synthetic and manure contributions), phosphorus (manure contributions), and potassium (both synthetic and manure contributions). Manure applications generally accounted for approximately 21% of the nitrogen applied (both pre- and post-BMP) and 50% of both the phosphorus and potassium applied after the storage facilities were functional.

Similar nutrient calculations were performed for subwatersheds QOC and QOD (Tables 3.7b, c). The area within the boundaries of QOC accounted for roughly 40% of the entire watershed. Throughout the monitoring project, approximately 30% of the Owl Run cropland was within this subwatershed. Fertilizer records showed an increase in the rate of manure and phosphorus application rates, and a decrease in the rate of nitrogen and potassium (Table 3.7b). Approximately 20% of the total nutrient loadings applied in the Owl Run watershed occurred within QOC during the post-BMP period, a decrease of approximately 4% from the pre-BMP monitoring phase. An estimated 20% of the Owl Run pasture land was within subwatershed QOC.

Subwatershed QOD is smaller in area than QOC, occupying close to 30% of the total watershed. Similar to QOC, this subwatershed also had approximately 30% of the Owl Run cropland, and nearly one third of the Owl Run pasture lands. QOD received approximately 30% of the total nutrient loadings, both synthetic and manure, applied within the Owl Run watershed during the pre-BMP period and increased to 40% during the post-BMP phase. The post-BMP period had an increased in both manure application rates and nutrient applications, demonstrated in Table 3.7c.

Table 3.7b. Annual Nutrient Applications on agricultural land within subwatershed QOC

	Manure	Nitrogen			Phosphorus			Potassium		
	Application Rate	Rate	Manure Nutrients	% manure nutrients**	Rate	Manure Nutrients	% manure nutrients **	Rate	Manure Nutrients	% manure nutrients
Year	m^3/ha	Kg/ha *	Kg/ha *		Kg/ha *	Kg/ha *		Kg/ha *	Kg/ha *	
1987	9	39	15	39	9	32	359	35	45	129
1988	9	54	15	28	49	31	64	60	44	74
1989	3	73	1	2	29	3	9	52	3	6
1990	6	52	6	12	19	8	44	33	12	38
1991	9	34	9	27	18	11	61	27	18	68
1992	18	44	12	28	23	15	68	44	31	70
1993	18	95	17	18	60	19	32	88	36	41
1994	25	115	21	18	63	26	42	69	49	70
1995	12	87	16	19	50	19	38	70	34	48
Pre-BMP Average	7	55	10	23	29	22	144	49	31	70
Post-BMP Average	15	71	14	20	39	16	47	55	30	56

* rate is calculated based on cropland area

** % manure nutrients = manure nutrients / nutrient rate * 100

Table 3.7c. Annual Nutrient Applications on agricultural land within subwatershed QOD

Year	Manure Application Rate m^3/ha	Nitrogen Rate Kg/ha *	Nitrogen Manure Nutrients Kg/ha *	Nitrogen % manure nutrients**	Phosphorus Rate Kg/ha *	Phosphorus Manure Nutrients Kg/ha *	Phosphorus % manure nutrients	Potassium Rate Kg/ha *	Potassium Manure Nutrients Kg/ha *	Potassium % manure nutrients
1987	19	118	29	24	26	60	230	75	85	113
1988	19	78	32	40	24	66	277	68	94	137
1989	19	125	6	5	47	8	18	89	16	18
1990	26	166	26	16	82	35	42	139	57	41
1991	20	112	22	19	37	27	73	86	53	62
1992	41	157	31	20	95	40	42	181	81	45
1993	45	109	41	37	85	49	58	165	94	57
1994	35	147	34	23	79	41	52	90	80	88
1995	23	138	77	56	84	61	72	147	117	79
Pre-BMP Average	19	107	22	23	32	45	175	78	65	89
Post-BMP Average	32	138	38	28	77	42	57	135	80	62

* rate is calculated based on cropland area
** % manure nutrients = manure nutrients / nutrient rate * 100

Monitoring system & data collection

The previous chapter included a discussion of various types of designs for monitoring projects. The Owl Run monitoring project was planned within the framework of a before/after data collection and analysis investigation. 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 collected, which was utilized to assess the effectiveness of the management practices through evaluating water quality improvements. Specific elements of the monitoring system included: wet and dry weather physical and chemical monitoring of surface and ground water; 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 aspect of surface runoff was nutrients, including both soluble and sediment-bound nutrients, organic chemicals, insecticides, and herbicides.

Four surface water monitoring sites were established within the Owl Run watershed (Figure 3.2). Six pre-existing private wells were employed to monitor ground water quality. However, after 12 months of data collection, the ground water monitoring was discontinued, as no water quality impairments were detected. Station QOA (A) was at the outlet of the watershed and the data collected at this site was intended to illustrate the overall response of the 1163 ha basin to the implementation of the BMPs. The runoff collected at site QOB (B) (45 ha) was installed as a means by which to exclude the urban runoff from the town of Calverton, Virginia. QOC (C) collected mainly agricultural runoff and was installed to demonstrate the efficiency of cropland BMPs in reducing nonpoint source pollution throughout the 462 ha subwatershed. The final station, QOD (D), drained 331 ha of land including runoff from two of the five dairy operations within the watershed. This monitoring station was intended to evaluate the effectiveness of intensive animal waste BMP implementations on stream water quality (Mostaghimi et al., 1989).

Streamflow and meteorological instrumentation installed in the watershed included: 4 water quality samplers, 8 recording raingages, meteorological instruments to record pan evaporation, ambient temperature, humidity, solar radiation, wind speed, and wind direction, and a precipitation sampler for monitoring the water quality of precipitation. Water quality samples were collected at every 6 cm change in the stream stage. ISCO (1979) samplers were installed at all stations and were controlled by 21x microloggers (Mostaghimi et al., 1989).

A 5:1 Virginia broadcrested V-notch weir was used to measure streamflow at QOA for low-flow control while 3:1 Virginia broadcrested V-notch weirs were used at QOC and QOD. At these three stations, rectangular broad-crested weirs were used over the flood plains to accommodate very high flows. At QOB, runoff was measured using a calibrated pipe culvert. Water level at the stream was measured using an FW-1 Belford (Friez FW1) recorder (Figure 3.3) equipped with timer gears and modified with a potentiometer. This allowed the stage to be sensed electronically by the Campbell Scientific 21x microloggers situated at each station. The 21x micrologger enabled data to be recorded simultaneously from multiple instruments. The recorded data was accessible by telephone lines or directly by portable computers. Data were collected continuously both on strip charts and electronically. Data collected on strip charts were digitized and stored in the database for further analysis (Mostaghimi et al., 1989).

The surface water monitoring stations have no base flow during dry weather, thus any runoff received is due primarily to storm events. The data collected in the watershed included precipitation in terms of quantity, quality and intensity, evaporation, wind speed and direction, solar radiation, air temperature, and relative humidity (Mostaghimi et al., 1989). Automatic water quality samples were used to collect discrete runoff samplers for chemical analysis. Stage recorders and data loggers measured the quantity and rate of runoff (Mostaghimi et al., 1989). Raingages were located at sites POA through POH (Figure 3.2) to collect precipitation data.

Rainfall intensity and amount were measured using continuous recording weighing raingages and tipping bucket raingages, both of which were equipped with digital recorders.

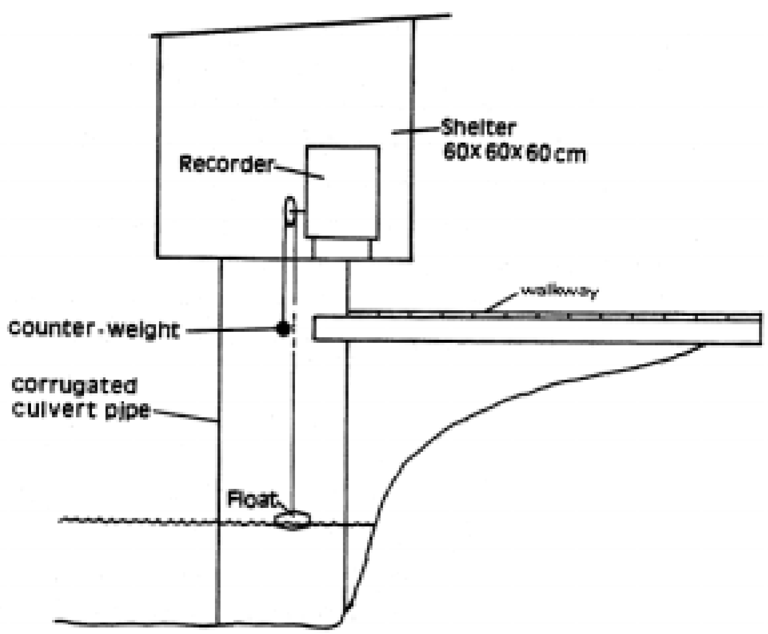


Figure 3.3. Typical recording stage-gage installation (Mostaghimi et al., 1989)

Biological sampling was initiated at station QOA and QOB during August of 1986 and in December 1986 at the other surface water monitoring stations (QOC and QOD). The biological monitoring of Owl Run included bimonthly grab sampling of the surface waters at the respective monitoring stations as well as quarterly sampling conducted for substrate colonization of algae, protozoan, and related microorganisms (Mostaghimi et al., 1989). Substrate colonization occurred on artificial substrates placed in the streams of the Owl Run watershed. The colonization of the substrates allowed investigators to compare communities of a known age within their natural habitat. Micro-fauna and flora which collected on the substrates included protozoan, algae, bacteria, fungi, rotifers, nematodes, oligochaetes, copepods, as well as insect larvae and cladocerans (Mostaghimi et al., 1989).

Laboratory Analysis Methods

The bacteriological grab samples were collected at the respective monitoring stations, immediately put on ice, and stored at 4^0C until analyses could be performed. All bacteriological analyses occurred within 24 h of sample collection, which is in accordance with the APHA prescribed methods (APHA, 1995). The Water Quality Laboratory at Virginia Tech performed the analysis for fecal coliform (FC), total coliform (TC), and fecal streptococcus bacteria (FS) when the project was first initiated. From September, 1993 through September, 1995, biological analysis was conducted at the Department of Biology at the Pennsylvania State University. Biological analysis then moved back to the Virginia Tech Water Quality Laboratory for the remainder of the project. Identical QA/QC procedures were employed at all laboratories.

Initially, the membrane filtration technique for fecal coliform analysis was performed according to the American Public Health Association's Method 909 (APHA, 1985). From January, 1988 until the end of the project monitoring, fecal coliform analysis was conducted according to the multiple tube fermentation technique (APHA, 1995). This latter method allowed for the analysis of total coliform bacteria as well which, prior to this data, was not reported. Both methods for fecal coliform enumeration provide bacterial densities, however the reported units are different (colonies / 100 mL and most probable number (MPN) / 100 mL, respectively). The last several bacterial water quality samples taken during 1987 (September through December) used both methods for fecal coliform analysis—seven data points in all. The results of these fecal coliform enumerations were statistically compared using the two sample t-test assuming equal variance. The resulting p-value (p= 0.479) indicated that the two data sets were equivalent. Thus, for the sake of consistency, all fecal coliform data is presented in units of MPN / 100 mL.

Testing of FS was conducted according to APHA's Method 910 (APHA, 1985). Also included in the laboratory analysis was protozoan quantification and determination, chlorophyll a, and ash free dry weight (AFDW) testing. Microscopic viewing and standard keys were employed to identify protozoan to a practical taxonomic level, most often species. This analysis also established the richness of the protozoan species (Mostaghimi et al., 1989). Measurements of chlorophyll a were taken using a spectrophotometer and according to standard methods, Method 1002 G (APHA, 1985). The resulting measurements were indicative of biomass. Community gross productivity was determined by the AFDW measurements which were conducted according to a modified standard method, 1002 H (APHA, 1985).

Quality Assurance / Quality Control

A lack of organization and/or method to one's data collection can result in data which is not scientifically defendable, rendering it unusable. In order to avoid such a situation, all data collection conducted throughout the duration of the Owl Run monitoring project followed the Quality Assurance / Quality Control Plan (Mostaghimi, 1989).

This document includes standard techniques for the design and upkeep of hydrologic research as suggested by Brakensick et al. (1979) as well as peers and researchers throughout the country (Young, 1985; Mitchel, 1985). The plan details the sampling and analytical procedures to be followed for each aspect of data collection. Table 3.4 and 3.5 provide quality standards of both field and laboratory data which were implemented to ensure that scientifically defendable data were collected.

Table 3.8 Data Quality Standards of Field Data (Mostaghimi, 1989)

Measurement Parameter	Accuracy	Precision	Completeness	References Used For Accuracy Calculations
Rainfall	4%	0.01 inch	80%	laboratory calibrated weights graduated pipette (with an equivalent 0.001" rainfall graduation
Stage				
Stream	0.01 foot	0.0002 foot	95%	land surveyor's level hook gage
Evaporation Pan	0.01 foot	0.0002 foot	95% [1]	hook gage
Temperature				
Air	$1.6\,^0$ C	$0.1\,^0$ C	95%	laboratory grade thermometer with $0.2\,^0$ C resolution
Soil	$1.6\,^0$ C	$0.1\,^0$ C	80%	same as above
Stream	$2.0\,^0$ C	$0.1\,^0$ C	95%	same as above
Time, Data Archival	5 minute	1 second	95%	digital watch referenced to University mainframe clock and observed to be accurate within 1 second per month
Time of				
Rainfall samples	10 minutes	1 second	90%	same as above
Wet weather stream samples	5 minutes	1 second	90%	same as above
Insolation	50 W/sq. M	0.2 W/sq. M	95%	laboratory calibrated/ laboratory stored radiometer
Wind direction	4 degrees	0.007 degrees	90%	land surveyor's compass
Wind speed	3 MPH		90%	manufacturers calibration
Relative humidity	10 % RH	0.025 RH	70%	sling psychrometer

[1] Evaporation pan is in operation during spring, summer and autumn only

Table 3.9 Data Quality Standards of Laboratory Data (Mostaghimi, 1989)

Parameter	Detection Limit (mg/L)	Percent Recovery	Precision (mg/L)	QA Protocol *
Ammonia (NH3 - N)	0.01	98-102% recovery	+/-0.06	1 duplicate per 20 samples 1 EPA QA-QC standards per 40 samples 1 spike per 40 samples 1 blank run daily
Nitrate (NO3 - N)	0.05	96-100%	+/-0.026	1 duplicate per 20 samples 1 EPA QA-QC standards per 40 samples 1 spike per 40 samples 1 blank run daily
Orthophosphate (PO4 - P)	0.01	89-94%	+/-0.013	1 EPA QA-QC standards per 40 samples 1 spike per 40 samples 1 blank run daily
TKN	0.1	97-101%	+/-0.126	1 duplicate per 17.5 samples 2 EPA QA-QC standards per 35 samples 1 spike per 35 samples 1 blank run daily
Total-P	0.05	91-94%	+/-0.056	1 duplicate per 17.5 samples 2 EPA QA-QC standards per 35 samples 1 spike per 35 samples 1 blank run daily
Total suspended Solids	0.02	+/-5% relative error	+/-0.74	1 duplicate per 40 samples 1 blank per 40 samples 1 EPA standard per 200 samples
COD	10	+/-5% relative error	+/-4.23	1 duplicate for each sample 1 EPA standard per 200 samples

Table 3.9 Data Quality Standards of Laboratory Data (Mostaghimi, 1989), continued

Parameter	Detection Limit (mg/L)	Percent Recovery	Precision (mg/L)	QA Protocol *
Total Coliform	< 2 / 100 mL	NA	NA	1 site duplicate per sampling 1 blank (water) 1 blank (media) presumptive test for each site confirmed test for each site
Fecal Coliform	< 2 / 100 mL	NA	NA	1 site duplicate per sampling 1 blank (water) 1 blank (media) presumptive test for each site confirmed test for each site
Fecal Streptococcus	0 / 100 mL	NA	NA	1 site duplicate per sampling 1 blank (water)

* The QA protocol was designed as a minimum allowed QC procedures to follow based on the data quality objectives for this project. This plan was developed using the references listed below. Detection limits are lab values based on the height of recorder noise at maximum sensitivity. (Gas Chromatograph, Dr. H. McNair, 1985 ACS Shortcourse publication).

Handbook for Analytical Quality Control in Water and Wastewater Laboratories, USEPA, 1979.
Handbook of Quality Assurance for the Analytical Chemistry Laboratory. J. P. Dux (VNR Co. Inc.), 1986
Quality Assurance of Chemical Measurements. J. K. Taylor (Lewis Pub. Inc.), 1987
Microbiological Methods for Monitoring the Environment: Water and Wastes, USEPA, 1978
Standard Methods for the Examination of Water and Wastewater, 19th ed., 1995
Modern Food Microbiology, 5th ed., James M. Jay, 1996

BMP Implementation

The Owl Run watershed underwent comprehensive pre-BMP monitoring for approximately 2 1/2 years. Beginning in June 1988 and continuing over approximately two years, a combination of structural and agronomic BMPs were installed. Major structural BMPs included manure storage facilities, extensive fencing, stream crossings, and watering troughs. Table 3.6 presents the numerous structural BMPs which were installed, including location, date of completed installation and extent of implementation. Major agronomic BMPs include conservation tillage, grassed waterways, and nutrient management plans.

The overall cost for BMP installation was nearly half a million dollars, however, livestock producers and land owners did not have to bear the financial burden alone. The implementation of BMPs was done on a volunteer basis and those who agreed to participate in the monitoring program were financially assisted with the Virginia cost-share program. Under this program, land operators can receive state and federal money to aid in the financial responsibility of BMP installation. Each year, the Virginia Department of Conservation and Historic Restoration, Division of Soil and Water Conservation publishes the "Virginia Agricultural BMP Cost-Share Program Manual" which details participation requirements and fund allocation procedures.

Table 3.10 BMP installations within the Owl Run watershed

Date Installed	Farm / BMP Component	Quantity	Units
	Armstrong		
11/27/90	Fencing of pond & stream	6,600	m
11/27/90	Repair pond & spillway	1 unit	
	Jack Cassell		
9/14/88	Manure storage structure	1 unit	
	Day Brothers		
9/5/89	Diversion above pond	1,320	m
9/5/89	Fencing	4,518	m
9/5/89	Repair pond & spillway		
	Eastern View		
6/7/88	Field stripcropping	5.7	ha
6/7/88	Obstruction removal	0.4	ha
6/7/88	Field stripcropping	8.4	ha
10/30/92	Mulch for waterway	0.8	ha
6/7/88	Field stripcropping	8.5	ha
1/16/90	Waterway with 24" culvert	3,300	m
10/4/92	4 Strand barb wire fence	2,706	m
10/7/92	Barn gutters	1,320	m
10/4/92	Board fence access lane	396	m
10/4/92	Catch basin/12" roof drain	1,320	m
	Fencing at catch basin	198	m
9/25/89	Fencing	9,900	m
9/25/89	Fencing & seeding lot	2,640	m
10/4/92	Subsurface drain for waterway	5,280	m
10/30/92	Waterway	3,300	m
	Access lane from barn	462	m
10/20/89	Waterway	4 units	
6/7/88	Manure storage pit	1 unit	
1/16/90	Ramps added to pit	1 unit	
11/30/88	Watering trough	3 unit	

Table 3.10 BMP installations within the Owl Run watershed, continued

Date Installed	Farm / BMP Component	Quantity	Units
	Eley Farm		
	Fencing	9,900	m
	Stream crossing	2 units	
7/21/93	Well & trough	2 units	
	Findley Farm		
6/7/88	Field stripcropping	12.3	ha
10/20/89	Waterway	1 unit	
	Charles Gray		
9/13/89	Fencing	10,167	m
10/7/92	Stream crossing		
11/27/90	Repair pond & fence		
	Hi-Hope Dairy		
1/2/90	Manure storage structure	1 unit	
6/5/89	Manure storage structure	1 unit	
	Pete Laws		
12/13/88	Manure storage structure	1 unit	

Data Analysis

Comprehensive monitoring of the Owl Run watershed occurred over a ten year time span. Data collection included both pre- and post-BMP data. Daily precipitation and stream flow data were downloaded from the HAS data management system, located on the Virginia Tech mainframe computing system, and reduced to monthly averages. These data were statistically analyzed by applying the Kolmogorov-Smirnov two sample test. Biannual landuse records over the course of the monitoring project were compiled into yearly averages and distributed among six categories: farmstead, cropland, forest, pasture, inactive agricultural land, or other. The 'other' landuse category included 'no report' field responses (more common during the beginning of the data collection), ponds, vegetative waterways, and Critical Reserve Program (CRP) land, as these lands typically represented less than 5% of the watershed. Nonparametric trend analysis (Mostaghimi et al., 1998) was applied to the cropland and pasture landuse categories, as these two categories were of greatest interest in terms of BMP implementation.

Ten years of bacteriological data were collected from four surface water monitoring stations within the Owl Run watershed. There were a total of 12 bacteriological data sets collected—fecal coliform, fecal streptococcus, and total coliform data from each of the four surface water monitoring collections sites, A, B, C and D. Approximately 160 samples were collected over the course of the project at each of the sites, roughly distributed as 45 pre-BMP samples and 125 post-BMP samples. Since geometric means provide a more representative average for bacteriological data (APHA, 1995), this method was used to calculate all averages. Seasonal averages were determined, based on four, three-month intervals—winter, January through March;

spring, April through June; summer, July through September; and autumn, October through December. Geometric means were also used to compare the Owl Run water quality to the Commonwealth of Virginia surface water quality standards, available for fecal coliform bacteria only. Percent reductions and/or increases were examined from the pre- to the post-BMP period.

When statistically analyzing any type of data, a question of great importance is whether parametric or nonparametric techniques should be used for the data analysis. Parametric tests are powerful, but require a normally distributed data set. Nonparametric statistical methods, in contrast, are not bound by such distribution requirements. The distribution of all 12 data sets was statistically tested to determine if they followed a normal distribution. The Shapiro-Wilks test for normality was used within the SAS statistical software (SAS/STAT, 1990). The null hypothesis of this test is that the data are not normally distributed, and are proven to be normally distributed is the p-value is greater than 0.05. At an alpha (α) level of 0.05, the null hypothesis failed to be rejected in all instances. Thus, all of the bacteriological data sets failed to be normally distributed, which is typical of biological data (APHA, 1995). A logarithmic transformation was applied to each of the data sets (APHA, 1995) and the normality test repeated. Five of the 12 data sets were then normally distributed (Table 3.7). Note that two of the histograms from the non-normal data appeared to follow a Gaussian curve upon visual inspection despite the fact that this was not statistically proven. Because of this nearly equal split between normal and non-normally distributed data, both parametric and non-parametric statistical analyses were used in the evaluation of the Owl Run bacteriological data.

Table 3.11 Normality of log-transformed bacteriological data

Station	P values TC	FC	FS
A	**0.0746** [1]	**0.715**	0.0001
B	**0.1638**	0.0334	**0.1371**
C	0.0003	0.0053 *	**0.0452**
D	0.002	0.0002 *	0.0001

[1] **Bold** indicates normality.
* Appeared normally distributed upon visual inspection.

Walker (1994) outlines a variety of both parametric and nonparametric statistical techniques for assessing BMP impact on water quality. Since monotonic trends typically develop gradually over time, parametric regression analysis is a suitable statistical method which can be applied to water quality data (Walker, 1994). Step-wise multiple linear regression was thus applied to the log-transformed Owl Run bacteriological data using the SAS statistical analysis computer software (SAS/STAT, 1990). The general form of the regression model was as follows:

$$\text{log Bacteria} = \beta_0 + \beta_1 * Z + \beta_2 * \text{time} + \beta_3 \, (Z * \text{time}) \qquad (3.1)$$

where 'log Bacteria' is the natural logarithm of the measured FC, FS or TC bacteria, 'Z' is the BMP phase (0 for pre-BMP and 1 for post-BMP), 'time' refers to time in days, and β_0 through β_3 are fitted regression coefficients.

Since normality of the log-transformed data was not present among all the data sets, a rank transformation (Conover, 1980) was applied. During this transformation, the data are ordered from smallest to largest, and their measured value replaced with their rank order. This transformation is useful to reduce the influence of outliers on the data set. Regression analysis using the General Linear Model procedure (SAS/STAT, 1990) was then applied to the transformed data. Again, the general model of the regression equation was:

$$\text{Ranked Bacteria} = \beta_0 + \beta_1 * Z + \beta_2 * \text{time} + \beta_3 (Z * \text{time}) \quad (3.2)$$

where 'Ranked bacteria' is the rank order of the FC, FS and TC bacteria, 'Z' is the BMP phase (0 for pre-BMP and 1 for post-BMP), 'time' refers to time in days, and β_0 through β_3 are fitted regression coefficients.

As previously noted, approximately half of the bacteriological data sets failed to follow a normal distribution. Nonparametric statistical techniques are advantageous to use in such situations, as these tests have no underlying assumptions concerning the data distribution. A variety of nonparametric statistical techniques have been used by researchers (Walker, 1994; Mostaghimi et al., 1996; Hirsch et al., 1982; Hippel, 1988) to evaluate water quality data. The Seasonal Mann-Kendall (Mann, 1945; Kendall, 1975; Hirsch et al., 1982) was applied to the bacteriological data in order to examine any trends the data may exhibit. Three trend homogeneity tests were conducted to determine the homogeneity of trends among surface water monitoring sites, among seasons, and identify any site-season interaction. This was accomplished by using methods described by van Bell and Hughes (1984). The results of these tests should determine if the trends: are homogenous (i.e. all in the same direction) for site, for season; exhibit a site-season interaction; and if there is an overall watershed trend. The homogeneity of trends for site, season, and site-season interaction were discovered using the Chi-square test results. Finally, the Sen slope nonparametric slope estimator (Sen, 1968) was used to quantify any detected trends, whether overall or seasonal. All nonparametric trend analyses were completed using TREND (Mostaghimi et al., 1998). This statistical program is a modified version of an earlier routine, created by Engel and Gilbert (1987).

A non-parametric multiple comparison test was employed in order to compare bacteria levels among the four surface water quality monitoring stations. The Jonckheere-Terpstra test for ordered alternatives was used to make a statistical comparison of the bacteriological levels among the surface water monitoring stations. The null hypothesis was that the median bacteria level at all stations was equal. The alternative hypothesis was that station D had the highest level, followed by station B, station A, and station C. The lowest levels of fecal bacteria were expected at station C since the pond located just upstream of the monitoring station likely trapped any fecal bacteria which may have entered. Station D was thought to have the greatest bacteria levels as two of the five dairy operation are within this subwatershed.

Results and Discussion

Data collection from the Owl Run watershed was initiated in April of 1986 and continued through June of 1996. The pre-BMP monitoring period lasted for 39 months, while the post-BMP phase continued for the remaining 84 months of data collection. The overall project goal was to evaluate the effects of animal waste BMPs, installed throughout a watershed with complex landuse, on stream water quality. Although animal waste management practices were the focus of the study, numerous other BMPs including field strip cropping, conservation tillage, grassed waterways and alternative livestock water sources were also implemented within the basin. The goal of this research was to assess the BMP impacts on the bacteriological quality of surface waters. Throughout the watershed monitoring period, data on fecal coliform, fecal streptococcus, and total coliform bacteria were collected on a bimonthly basis. The data collected during this investigation allowed for: the characterization of the ambient microbial water quality of the watershed prior to the implementation of BMPs and a comparison between the pre- and post-BMP period data in order to evaluate BMP impacts upon water quality.

This chapter presents the results from the Owl Run bacteriological data collection and analysis. Background information such as landuse, precipitation, and runoff data are reported in order to aid in the characterization of the watershed prior to the BMP installations, as well as throughout the monitoring project. The data are compared with the Commonwealth of Virginia surface water quality standards to facilitate the assessment of the bacteriological quality of the Owl Run watershed both prior to and after BMP implementation.

Watershed Landuse Activities

The landuse activities within the Owl Run watershed were documented throughout the project lifespan. These data were then used to show the changes which occurred, due to the adoption of various management practices in conjunction with the monitoring project. The water quality data were compared to the landuse records in order to attribute changes in water quality to the landuse practices implemented in the watershed. Nonparametric trend analysis (Mostaghimi et al., 1998) was applied to the pasture and cropland annual landuse data, as discussed in the previous chapter.

Cropland trends were found to be heterogeneous, as station QOA had a positive trend, increasing at a rate of 8.2 ha/yr, station QOC exhibited no trend (p=0.937), and QOD had a decreasing trend in cropland, at a rate of 0.7 ha/yr. Pasture landuse trends were homogenous at all stations, increasing throughout the project monitoring. For the entire Owl Run watershed, the magnitude of the rate of increase in pasture land was estimated to be 10.0 hectares per year. Within subwatershed QOC and QOD, the estimated rates of increase were 7.3 ha/yr and 1.3 ha/yr, respectively.

Rainfall and Runoff

Nonpoint source pollution occurs as the direct result of numerous activities, agriculture being a major contributor. The diffusion of pollutants into the environment is a complex process with precipitation and overland flow being the driving forces behind NPS pollution. Precipitation cannot be controlled, as it is guided by the natural forces of climate. An examination of both the precipitation and runoff data collected during the decade-long monitoring is therefore essential to include in this discussion of NPS pollution data in order to fully understand the impact of BMPs on bacteriological water quality data.

Precipitation

Rainfall was fairly well distributed throughout the study site, with the majority of the rain occurring in the spring. (Mostaghimi et al., 1989) The precipitation data, collected from July 1986 through June 1996, was measured by continuous recording weighing raingages and tipping bucket raingages throughout the watershed, as previously discussed. After these data were collected and imported into the Hydrologic Analysis System (HAS) data management system (Carr et al., 1988) the THEISSAN routine was run to calculate a weighted average daily rainfall for the watershed. Based on these results, monthly totals were calculated and used in the data analysis.

The watershed experienced a 3% increase in monthly precipitation from the pre- to the post-BMP period (Figure 4.1). Figure 4.2 presents the monthly rainfall totals. Additional graphs detailing precipitation data can be found in Appendix A. The results of the Kolmogorov-Smirnov two sample test applied to the precipitation data failed to reject the null hypothesis ($p=0.431$) that the distribution of the pre- and post-BMP rainfall data tend to be similar. Hence, there was little evidence to suggest that the pre-BMP rainfall differs significantly from the post-BMP precipitation.

Runoff

Runoff rate and volume within the watershed were measured by the methods discussed earlier. Unlike precipitation, the runoff data were specific to each subwatershed monitoring site. Data collection for runoff began in April, 1986 at the watershed outlet and in May, August, and August 1986 at subwatersheds B, C, and D, respectively. The HAS system was used to store and manage the runoff data (Carr et al., 1988). The subroutine TOTALS was run with the collected data to produce daily runoff values. Monthly values were calculated and used in the data analysis.

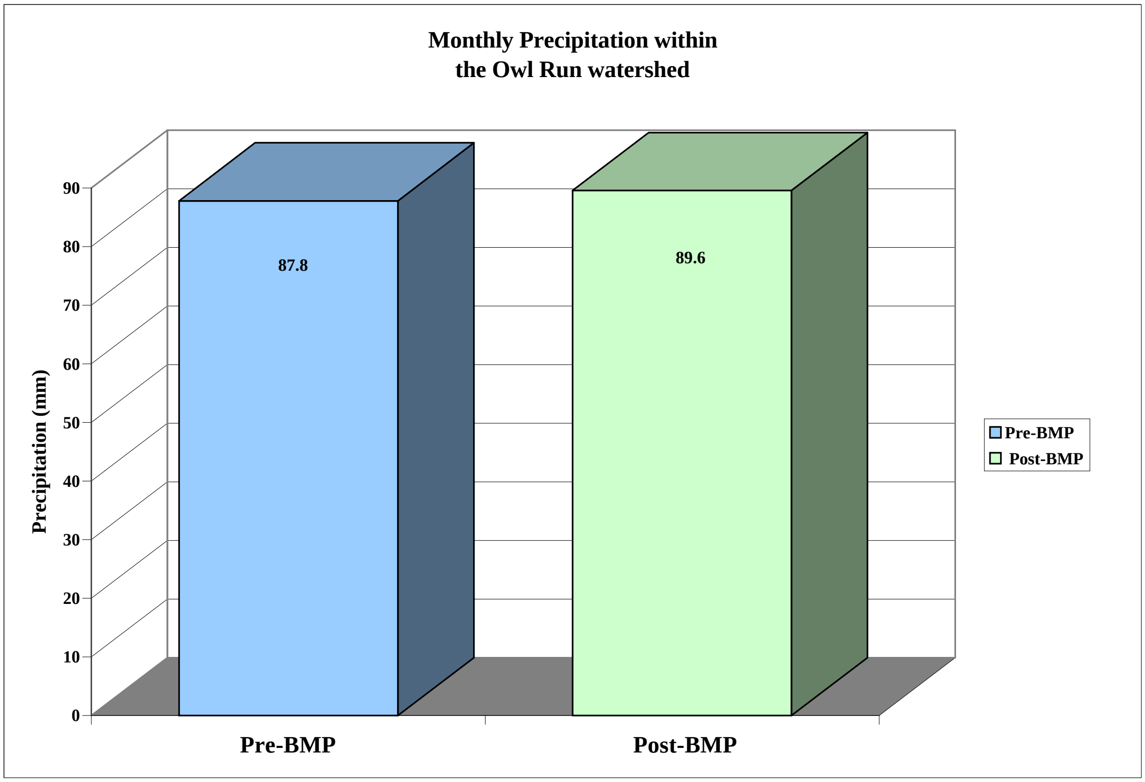


Figure 4.1 Comparison of pre- and post-BMP monthly precipitation

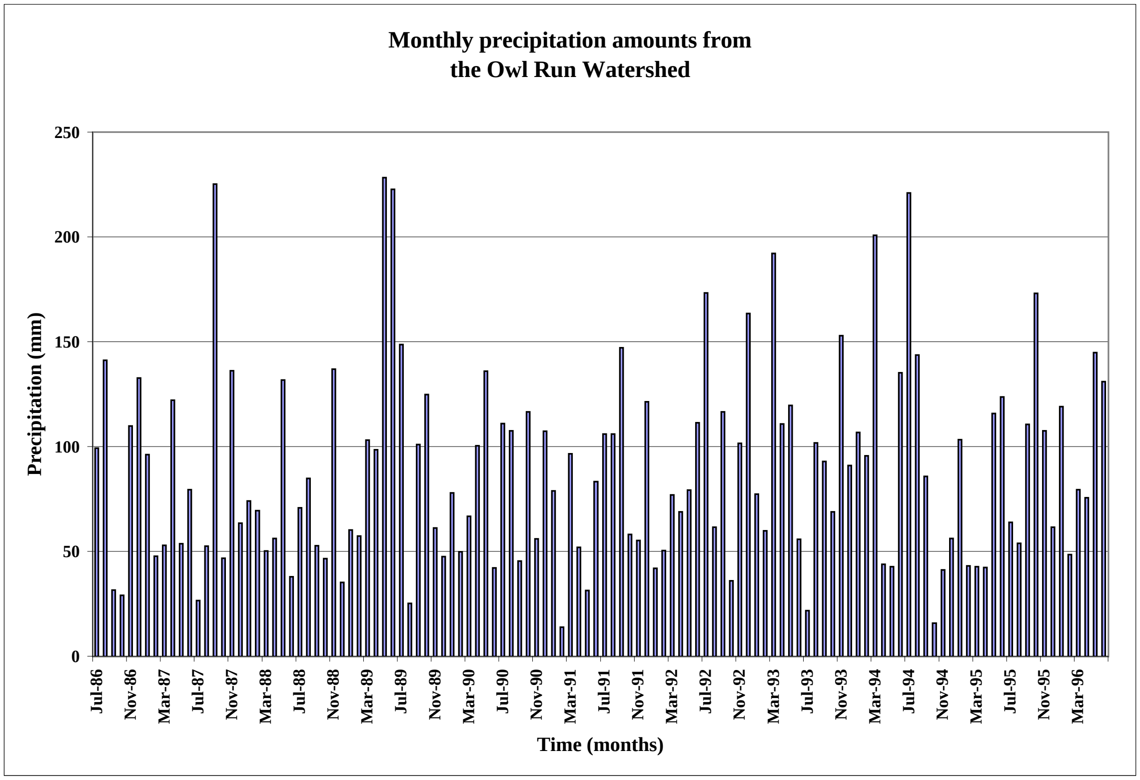


Figure 4.2 Monthly precipitation totals

Average monthly runoff at station QOA, the watershed outlet, increased by 39% from the pre- to the post-BMP period (Figure 4.3). Increases were observed at the other surface monitoring stations as well. Within subwatershed QOB, runoff volume increased by 40%, QOC 38%, and QOD 16%. The Kolmogorov-Smirnov two sample test indicated no statistical differences between the pre- and the post-BMP periods at any monitoring site except Station QOC. At this site, there is evidence to suggest that the monthly runoff totals tended to be greater during the post-BMP period than during the pre-BMP period ($p=0.13$). Graphical representation of the monthly runoff totals for stations QOB, QOC, and QOD can be found in Appendix A. Although the precipitation amounts were not statistically different for the pre- and post-BMP periods, the rainfall pattern and/or intensity may have caused runoff volume to increase from the pre- to the post-BMP period.

Bacteriological Data

Water quality grab samples from the four surface water monitoring sites, A, B, C and D, were collected bimonthly and analyzed for fecal coliform, fecal streptococcus, and total coliform bacteria over a ten year period. The data are presented, along with the results of both the parametric and nonparametric statistical analyses.

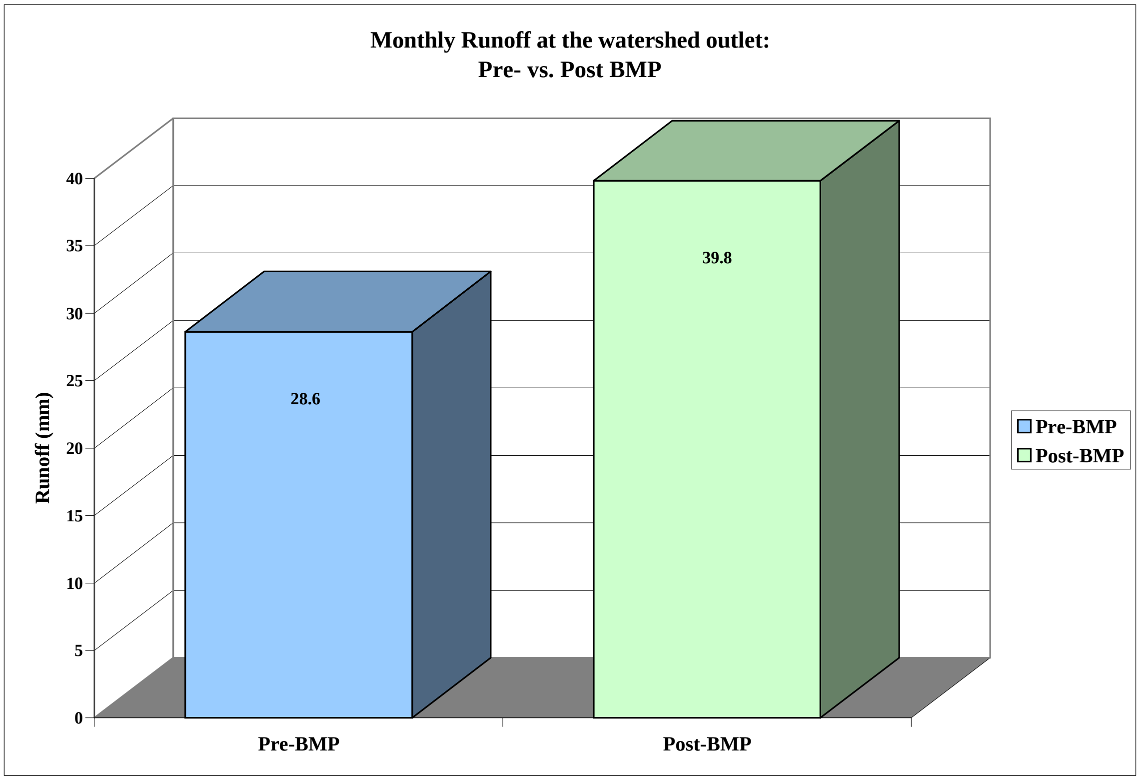


Figure 4.3 A comparison of pre- and post-BMP monthly runoff at the watershed outlet

Fecal Coliform Bacteria

Fecal coliform analysis was included as a component of the biological monitoring study at Owl Run. The bimonthly surface water quality samples collected at station QOA, the watershed outlet, allowed for examination of the overall watershed response to the combination of BMPs implemented throughout the catchment. Since the majority of streams within Owl Run are intermittent, during the late summer and early autumn, the streambeds were often dry, preventing the collection of water samples. A total of 178 fecal coliform samples were obtained and analyzed, 54 belonging to the pre-BMP and 124 to the post-BMP monitoring phases. Samples were classified by season as previously defined. Geometric means were calculated for each season and used in the data analysis.

Figure 4.4 compares the mean (geometric) fecal coliform values of the pre- and post-BMP periods, both overall and seasonally, at the outlet of the Owl Run watershed. The watershed outlet had an overall reduction of 40% in FC densities from the pre- to post-BMP collection periods. Reductions were observed during each season, with the greatest reductions in FC levels occurring during the autumn (56%) and winter (51%). The spring and summer levels of fecal coliforms were reduced by 15% and 25%, respectively.

The fecal coliform data failed to follow a normal distribution, commonly demonstrated among microbiological data (APHA, 1992), and were therefore logarithmically transformed (APHA, 1992; Berthouex & Brown, 1994). Regression analysis of the log-transformed FC data is

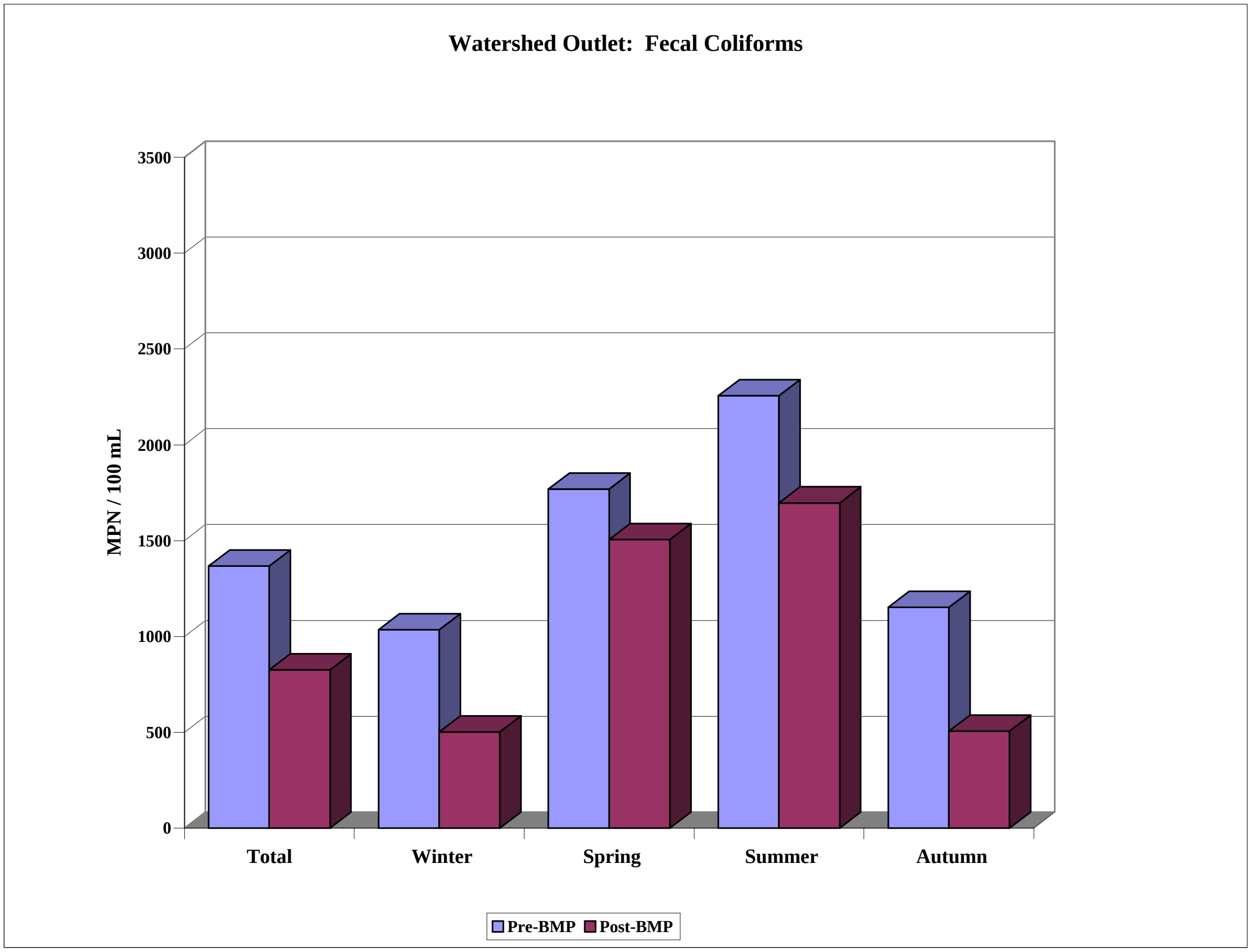


Figure 4.4 Mean fecal bacteria at the watershed outlet

visually represented in Figure 4.5. Both the pre- and the post-BMP periods are present in the regression line, as indicated. One will note that during the pre-BMP period, there appears to be an increase in FC levels, while the post-BMP period shows an obvious decrease in fecal coliform densities. A significant difference between the pre- and post-BMP period was observed when the data were statistically compared (p=0.0199). Identical regression analysis was applied to the rank-transformed data. The result of this analysis also showed a significant difference between the pre- and post-BMP periods (p=0.0119), which further supports the results of the log-transformed data.

Surface water sampling and fecal coliform analysis were conducted at subwatersheds QOB, QOC, and QOD identically to that at the watershed outlet. A total of 157 samples were collected and analyzed for fecal coliform bacteria at station B, 47 pre-BMP and 140 post-BMP samples. The overall fecal coliform levels at the outlet of subwatershed QOB increased 103% from the pre- to the post-BMP period (Figure 4.6). Seasonal increases were observed during the winter (209%), summer (745%), and autumn (156%) periods. A 23% decrease occurred during the Spring season. Regression analysis of the log-transformed fecal coliform data showed a significant difference when the pre-BMP period was compared with the post-BMP data (p=0.0001) (Figure 4.7). This finding was supported when regression analysis of the ranked data was performed (p=0.0008).

Throughout the monitoring of subwatershed QOC, 149 fecal coliform data points were acquired, 40 during the pre-BMP period and 140 during post-BMP. The fecal coliform levels increased

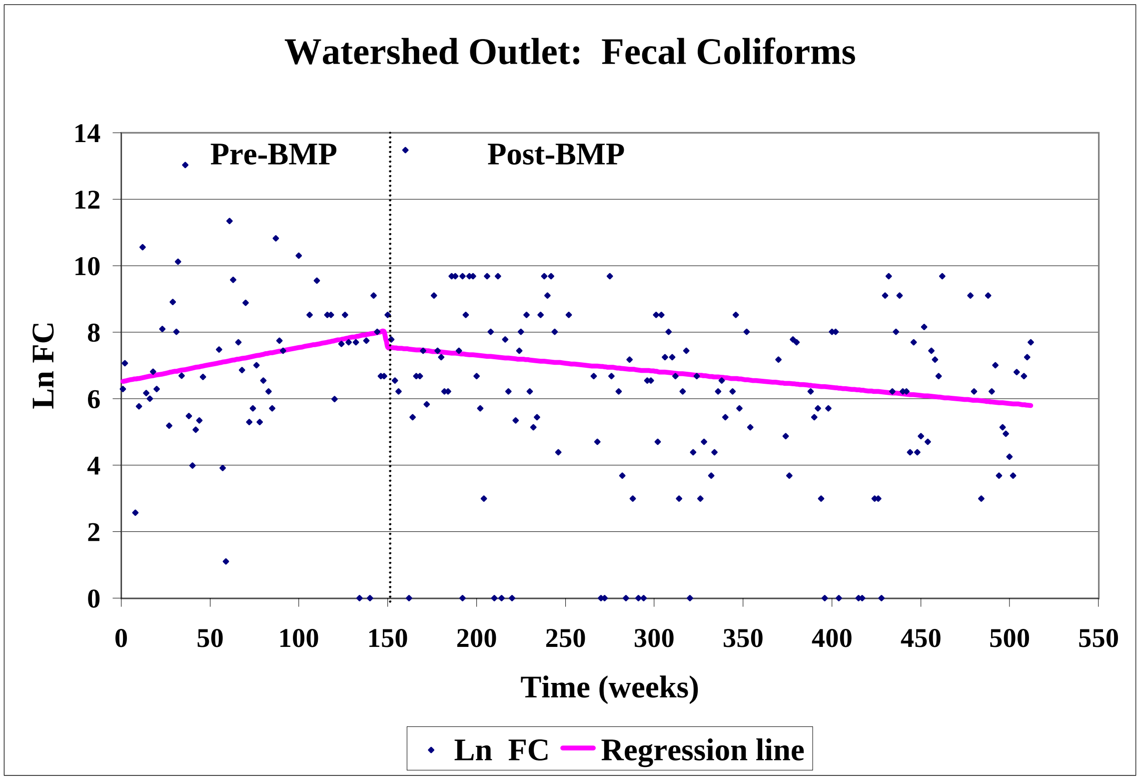


Figure 4.5 Fecal coliform regression at the watershed outlet

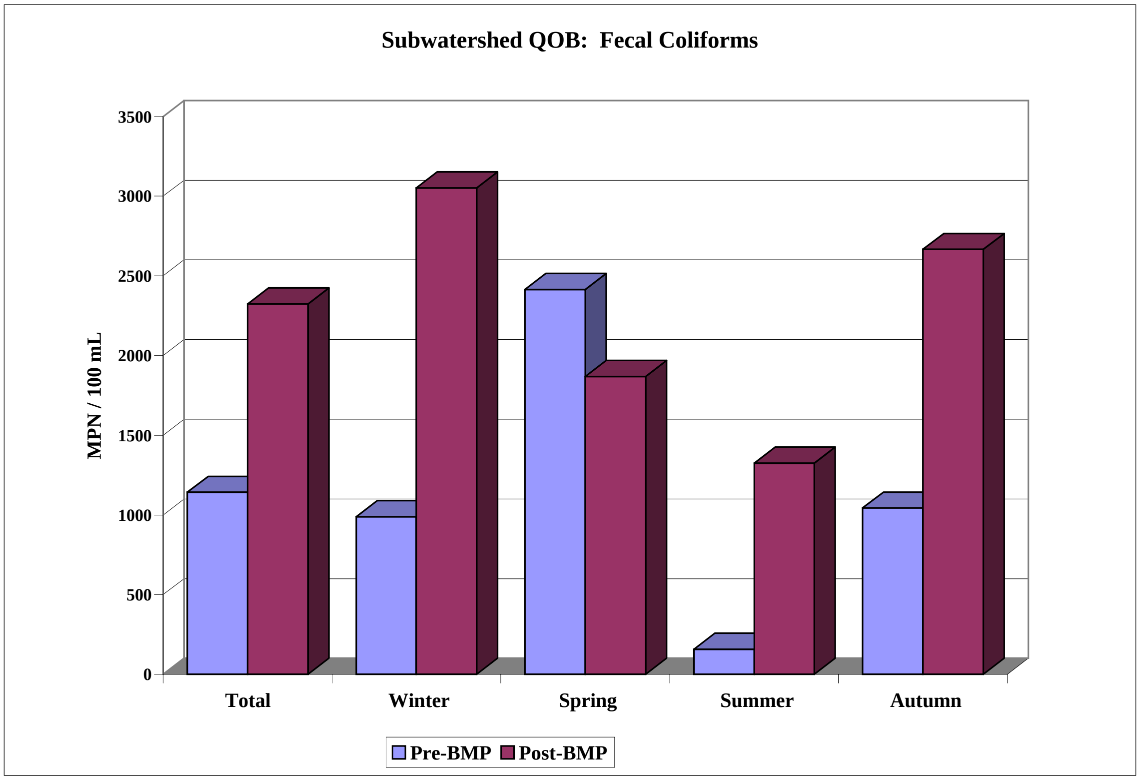


Figure 4.6 Mean fecal coliform bacteria from subwatershed QOB

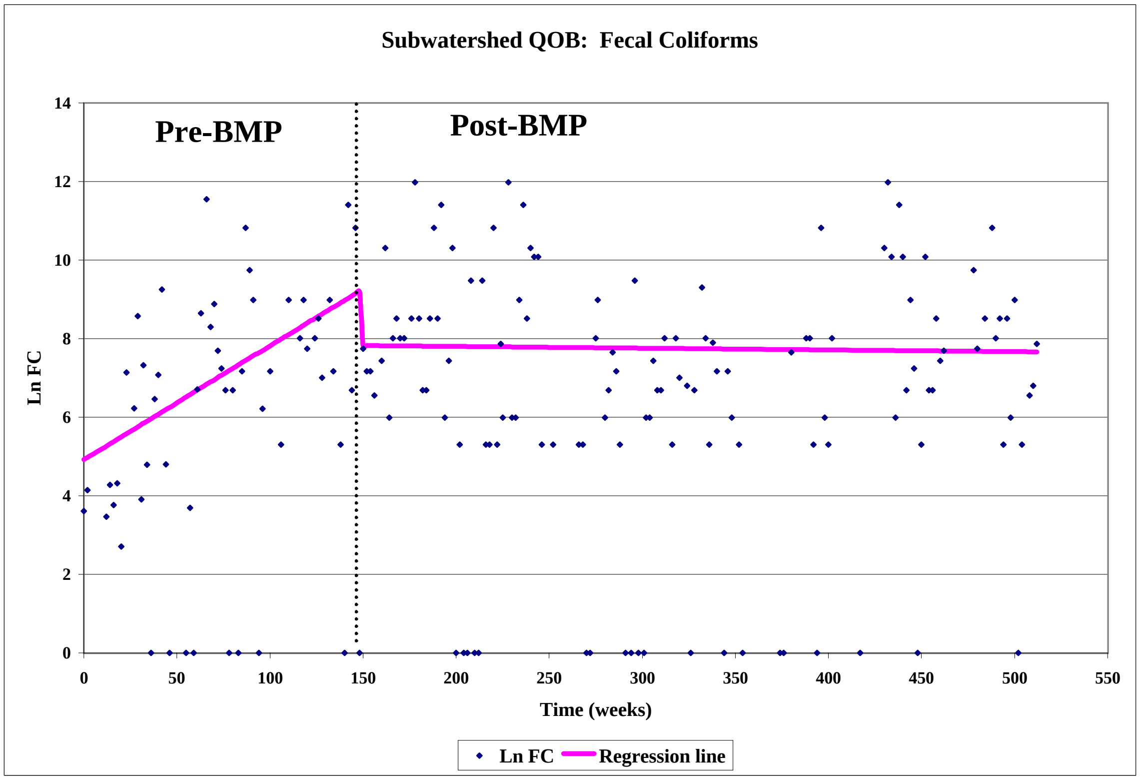


Figure 4.7 Fecal coliform regression of subwatershed QOB

94% over the course of the monitoring project at the outlet of subwatershed QOC (Figure 4.8). Seasonal increases in FC levels occurred during the winter (433%), spring (99%), and summer (112%) seasons, while a 19% reduction in FC levels was seen during the autumn months. Regression analysis of the log transformed FC data showed a statistical difference between the pre- and the post-BMP periods (p=0.0333) (Figure 4.9). This is not supported by the regression analysis using the ranked data (p=0.3792). This is one of two instances when the regression analysis using the rank-transformed data is not in agreement with the log-transformed regression analysis.

During the monitoring of subwatershed QOD, a total of 156 FC data point were obtained—the distribution of pre- and post-BMP data was 42 and 112 samples, respectively. Over the course of the surface water quality monitoring, fecal coliform bacteria increased 9% at site D. Seasonal increases occurred during the winter (24%) and summer (1015%), while FC levels decreased 16% during the spring and 8% during the autumn months (Figure 4.10). One should view the extremely large summer increase with caution. Due to the dry streambed conditions which were typical of the late summer months, only two surface water samples were available at QOD during the pre-BMP summer season, and 14 samples were collected and analyzed post-BMP. Typical pre- and post-BMP data sets during the other seasons at the QOD subwatershed averaged 20 and 52 samples, respectively. Basing the summer pre-BMP average on only two data points could be poorly representing the ambient water quality and therefore misleading. Therefore, the lack of adequate samples during the pre-BMP period should be considered when evaluating the apparent large increase in FC levels at QOD during the summer.

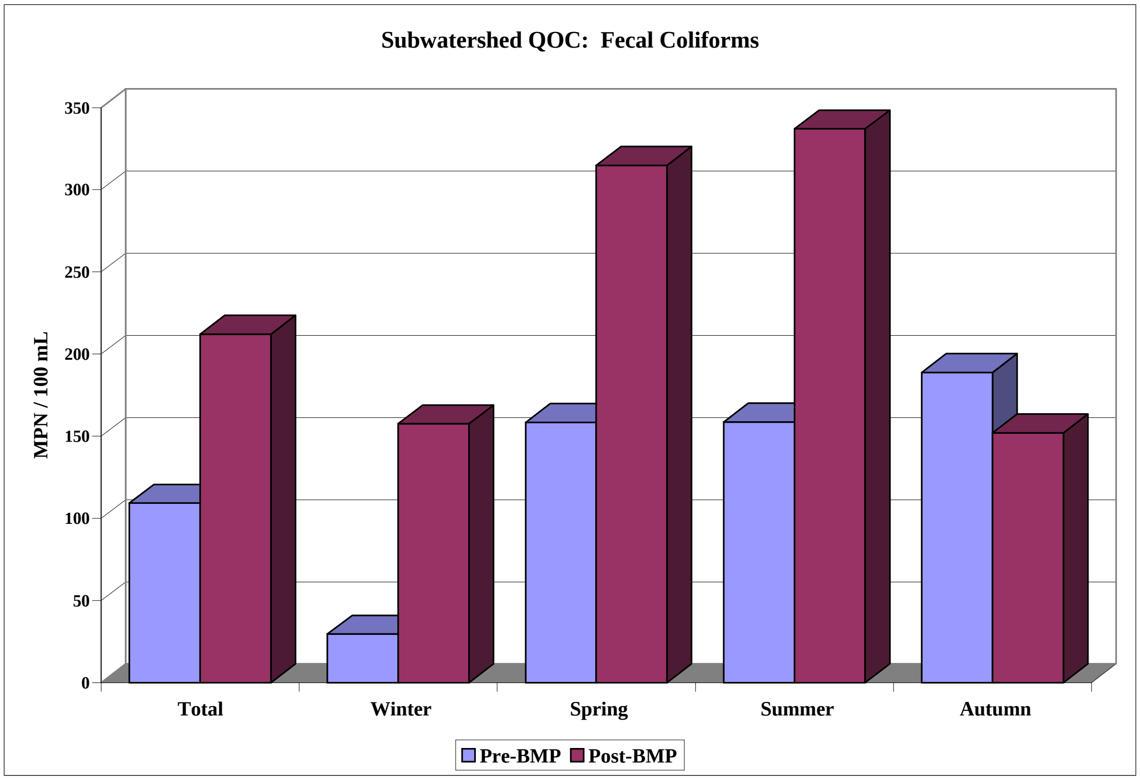


Figure 4.8 Mean fecal coliform bacteria from subwatershed QOC

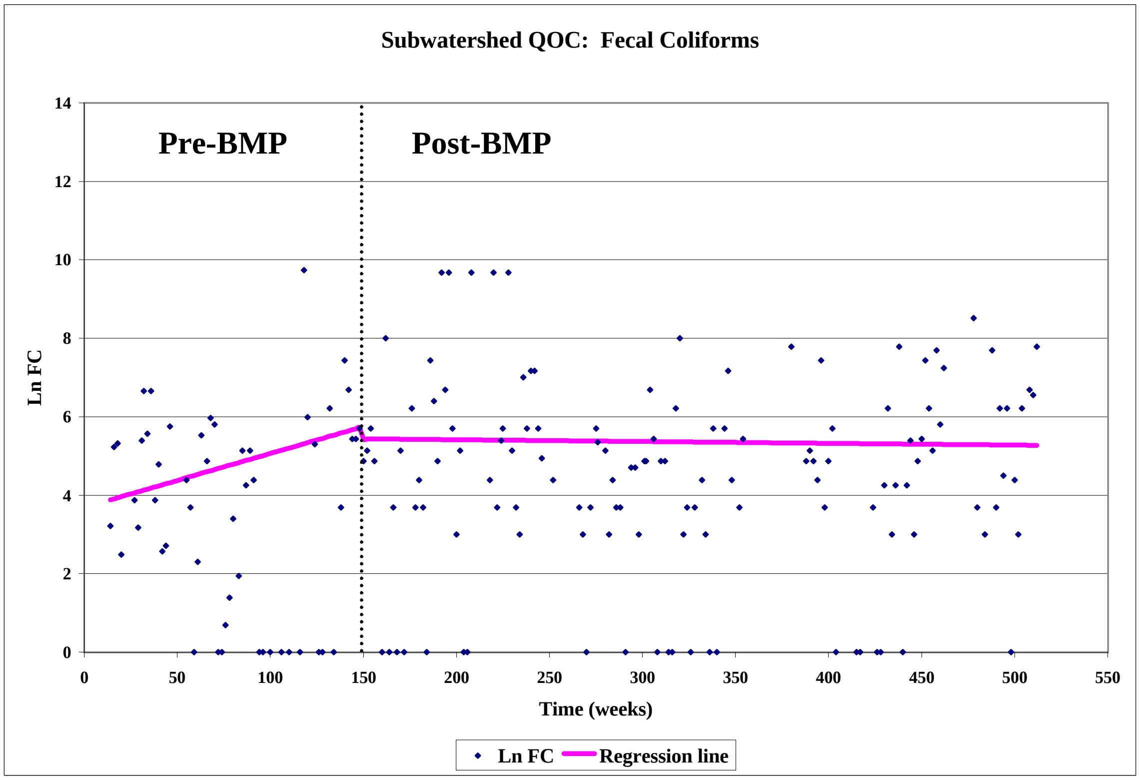


Figure 4.9 Fecal coliform regression of subwatershed QOC

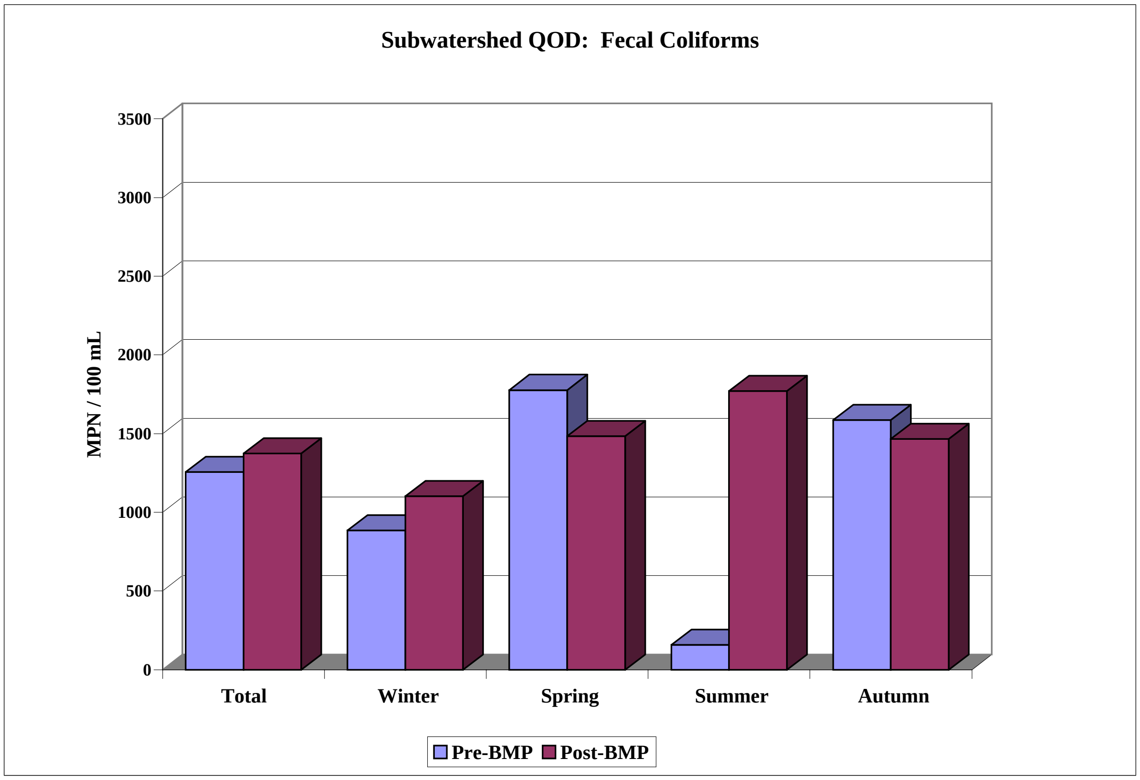


Figure 4.10 Fecal coliform bacteria from subwatershed QOD

Regression analysis of the log-transformed FC data showed a statistical difference between the pre- and post-BMP data at station D (p=0.0197) (Figure 4.11). This finding was not supported in the regression analysis of the ranked data (p=0.2653), the second of two cases when the results of the two regression analyses were not in agreement.

The nonparametric trend analysis which was applied to the fecal coliform data showed homogenous trends for both season (p=0.941) and station (p=0.221). No interaction between season and station was discovered (p=0.784). No trends were evident overall, at any station, or for any one season. It should be noted, however, that lack of sufficient data during the summer and autumn seasons prohibited any seasonal trend analysis for these two periods.

The null hypothesis was rejected in favor of the alternative hypothesis using the outcome of the Jonckheere-Terpstra test for ordered alternatives (p=0.000). This indicates there is at least one strict inequality in the expression 'C≤A≤B≤D' describing the levels of fecal coliform bacteria among the monitoring stations. Most probably, the inequality is between station C and B, due to the sizeable pond located just upstream from the QOC monitoring station. These results are in agreement with the consistently lower fecal coliform concentration observed at C, which were likely influenced by the presence of the pond. Fecal coliform bacteria were presumed to be low at the watershed outlet due to the effects of dilution. Subwatershed QOB did not receive as extensive BMP implementation as elsewhere within Owl Run, and stream water quality was influenced by urban runoff and possibly faulty septic systems and other human influences. Finally, station D was expected to have the greatest amount of fecal coliform bacteria since the

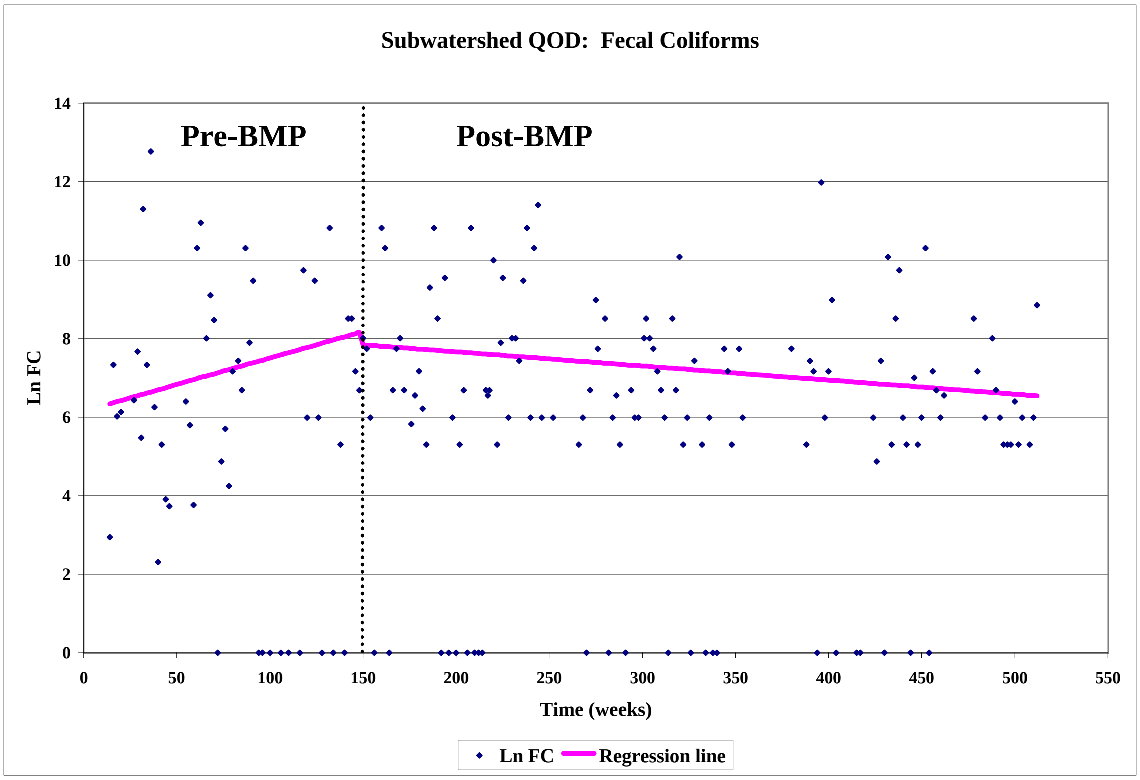


Figure 4.11 Fecal coliform regression of subwatershed QOD

small amount of land it drains supports two of the five dairy operations within the Owl Run watershed.

The Owl Run watershed outlet had an overall reduction in mean fecal coliform levels, with the largest seasonal reductions during the winter and autumn. This is statistically supported by the results of the regression analyses. Reductions in bacterial levels were anticipated for several reasons. First, the animal waste storage facilities, which were installed as a component of the research, promoted pathogen die-off by providing a hostile environment for the organisms. Second, the holding facilities provided for approximately six months of manure storage which allowed the land operator greater flexibility for land application. This flexibility included proper climatic conditions, soil temperature, and vegetative cover for nutrient uptake. Finally, with the waste material being stored over the colder months, this meant less manure application during the winter and autumn, and consequently more during the spring and summer. Thus, the greater reductions during the winter and autumn seasons were expected and the smaller percent reductions during the spring and summer are not surprising.

Despite the overall decrease in fecal coliform levels seen at the outlet of the Owl Run watershed, overall mean FC levels at each of the subwatersheds increased. Among all the stations, QOB had the largest relative increase in fecal coliforms. However since this drainage area receives primarily urban runoff, these elevated levels could have been influenced by faulty septic systems and/or other anthropogenic sources of fecal contamination. Increases occurred at subwatershed QOC, however, this station consistently had the lowest levels of fecal coliform bacteria, both overall and seasonally. This was to be expected as this subwatershed is primarily cropland and does not support the extent of livestock operations found elsewhere in the watershed. Also present just upstream of the C monitoring station is a pond, 1.1 ha in size. The presence of this pond could possibly influence the fecal coliform levels detected at the subwatershed outlet by accumulating fecal coliform bacteria within it. Station QOD, where two dairy operations contributed to the storm water runoff, had increases in FC levels both overall and during two of the four seasonal averages. No pattern was observed among the seasonal averages in terms of reductions or increases in fecal coliform bacteria. This is somewhat unexpected for reasons concerning the function and usefulness of the animal waste storage facilities discussed previously.

Regression analysis was used to compare the pre- and post-BMP fecal coliform data and determine if there was a statistical difference between the two data sets. The fecal coliform data were transformed both logarithmically and rank-ordered, and identical regression techniques were applied. The results of the two analyses were in agreement at stations A and B, however at station C and station D the rank-order regression did not support the log-transformed regression results. The logarithmic transformation is an established modification used when analyzing bacteriological data (APHA, 1995), whereas rank-transformation is not. Thus, the failure of the latter analysis to find a statistical difference between the pre- and post-fecal coliform data should be noted, but not heavily weighted, when evaluating the overall effectiveness of the BMPs at improving the bacteriological quality of streams receiving overland flow from agricultural lands.

Regression analysis of the log-transformed fecal coliform data showed upward trends during the pre-BMP period followed by downward tendencies during the post-BMP period at all stations. Statistical comparison of the pre- and post-BMP data at each station consistently showed a significant difference between these two periods. The results of these analyses suggest that the adoption of best management practices can have a notable impact on waters receiving storm-runoff from agricultural areas.

Prior to the Owl Run monitoring project, storage of animal waste was not typical. The waste materials were land applied with a weekly or sometimes even daily frequency, regardless of the ground temperature or presence/absence of a vegetative cover. Researchers have reported the risks associated with this application schedule (Crane et al., 1983; Eghball & Power, 1994) and suggest that storing waste material is an efficient means by which to reduce the potential for NPS pollution. Implementation of this management practice contributes to microbial die-off by providing a hostile environment for the fecal microbes, but also allows for more opportune climate and vegetative conditions for field application of the manure. The importance of proper weather conditions for field application of manure is reported in the literature by many researchers (Crane et al., 1983; Patni et al., 1985) and is further supported by the results from this investigation.

Neither the quantity of precipitation nor runoff were significantly changed from the pre- to the post-BMP periods, with the exception of station C. An increase in both cropland and pasture land occurred over the course of the investigation, as did an increase in animal waste management. Statistical analysis of the fecal coliform data collected at the outlet of the Owl Run basin shows a significant overall reduction in FC numbers over the course of the monitoring project. Some seasons showed reduction in fecal coliform levels, although no patterns in these reductions were noted. No trends, either overall, or on a station or season basis, were detected. The lack of any trends in fecal coliform bacteria could be the result of an insufficient amount of data. Spooner et al. (1992) reported that in order to detect trends in water quality data, 20 to 30 years of data are needed. Despite this claim, the Owl Run data suggest that the BMPs implemented throughout the watershed were effective in reducing fecal coliform levels in the streams. These results also help to substantiate the claim that waste storage, properly timing of animal wastes applications, and other BMPs can aid in the reduction of fecal bacteria present in agricultural runoff.

Virginia Water Quality Standards

The State Water Control Board in Virginia has set water quality standards in order to maintain existing "high quality waters and also provide for the restoration of impaired waters so they will permit reasonable public uses and will support the growth of aquatic life" (DEQ, 1997). Standards for microbial presence in surface waters vary from state to state, as does the type of indicator organism used as the foundation for the standards. Within the Commonwealth of Virginia, surface water quality standards are based solely on fecal coliform bacteria. According to the regulations, ". . . all surface waters with the exception of shellfish waters. . .shall not exceed a geometric mean of 200 fecal coliform bacteria per 100 mL of water for two or more samples over a 30 day period, or a fecal coliform bacteria level of 1000 per 100 mL at any time." (SWCB, 1992).

Thirty-day geometric means were calculated for the collected fecal coliform data at all monitoring stations in order to compare the watershed FC levels with the state standards. When possible, three data points were used in the calculation (i.e. when three samples occurred within 30 days, all three were used for the geometric mean calculation.) Otherwise, only two data points were used. In the event that there was not more than one sample taken within a thirty day period, a geometric mean was not calculated.

During the pre-BMP phase of the monitoring, the 30 day geometric mean of >200 fecal coliform bacteria / 100 mL standard was violated 94% of the time at the watershed outlet. Subwatersheds QOB, QOC, and QOD were also frequently in violation of this standard, 78%, 35% and 67% of the time, respectively. Post-BMP, the violations were reduced to 81% at the watershed outlet, while all the subwatersheds had an increase in violations. The surface waters at the Owl Run watershed outlet were in violation of not exceeding 1000 MPN/ 100 mL at any time a total of 52% during the pre-BMP phase of monitoring, reduced to 45% during the post-BMP monitoring. Subwatershed QOB had a slight increase in the amount of violations over the course of the monitoring, from 57% to 62%. Although QOC consistently had the lowest seasonal averages of FC bacteria, the violations in this subwatershed grew from 5% pre-BMP to 19% post-BMP. Despite the huge increase in violations of the 200/100 mL per 30 days at subwatershed QOD, a 2% decrease in violations occurred when using the 1000/100 mL standard. A visual comparison of these violations can be found in Table 4.1.

Table 4.1. Comparison of Owl Run data with VA water quality standards

	Geometric mean > 200 / 100 mL Within 30 days		> 1000 / 100 mL at any time	
Station	Pre-BMP % violations	Post-BMP % violations	Pre-BMP % violations	Post-BMP % violations
QOA	94	81	52	45
QOB	78	94	57	62
QOC	35	45	5	19
QOD	67	98	50	48

Limited BMP implementation occurred within subwatershed QOB, as this monitoring station was installed primarily to exclude urban runoff from the watershed outlet. Note that in Table 4.1, station QOB had the second largest amount of post-BMP violations under the 200/100ml standard, and the largest amount of violations under the other surface water quality standard. The high percentage of violations in the surface water quality standards from an urban area suggest that agricultural areas are not necessarily the main contributor to surface water quality impairments. Station QOC, which was primarily cropland and received approximately 20% of the total watershed manure applications, had the least amount of violations, although the pond was likely influential in these data. During the post-BMP period, station QOD was second to station B in exceeding 1000/100mL fecal coliform bacteria, but had the greatest amount of violations according to the 200/100mL fecal coliform standard.

Many researchers who have examined the topic of bacteria in overland flow have concluded that receiving water bodies exceed the existing water quality standards, whether the land is under intensive agricultural use or it is pristine land, undisturbed by human activity (Doran & Linn, 1979; Crane et al., 1983; Baxter-Potter & Gilliland, 1988; Neimi & Neimi, 1991). Because of the elevated frequency of violations seen from agricultural lands, many will argue that these lands should not be held to the state-established water quality standards, as the creation of these standards are based on point source discharges and the available control techniques for such effluents (Bohn & Buckhouse, 1989). For these reasons, many argue that water quality standards for diffuse pollution should not mirror those of point source discharges (Neimi & Neimi, 1991; Doran et al., 1981). Currently, however, this is not the case and thus BMPs are implemented within agricultural lands with the hopes of attaining what some would claim are practically impossible water quality standards.

Fecal Streptococcus Bacteria

Bimonthly sampling and analysis for fecal streptococcus bacteria was conducted as a part of the 10 year biological sampling at the Owl Run surface water monitoring stations. Although seasonally dry stream beds sometimes prevented water quality sampling and analysis, a total of 186 FS values were obtained at the watershed outlet, distributed as 52 pre-BMP and 134 post-BMP samples. Seasons were determined as previously discussed, and geometric means were calculated and used in the data analysis.

The watershed outlet experienced an overall reduction of 80% in fecal streptococci levels from the pre- to the post-BMP period (Figure 4.12). An even greater reduction occurred during the autumn (88%), winter (84%) and spring (86%). Summer fecal streptococci levels, however, increased by 25%.

The distribution of the collected fecal streptococci data was not normal. Like the FC data, the FS data were logarithmically transformed and statistically analyzed. Regression analysis of the log-transformed FS data did not indicate a significant difference between the pre- and post-BMP period (p=0.3752). A plot of the logarithmically transformed FS regression line is presented in Figure 4.13. The figure shows that during both the pre- and the post-BMP periods, the FS data appear to be decreasing. However, the large p value obtained when the slopes of the two periods were compared indicates that there was no statistical difference between the two data sets. Similar results were obtained when a regression of the ranked data was completed (p=0.4951).

Fecal streptococcus sampling and analysis occurred at the subwatersheds QOB, QOC, and QOD concurrently to that at the watershed outlet. There were 33 readings of fecal streptococcus levels during the pre-BMP data collection at station B, and 124 readings during the post-BMP monitoring. Overall FS levels at the QOB subwatershed outlet were reduced 62% from the pre- to the post-BMP period (Figure 4.14). Reductions occurred during every season, spring being the greatest (85%) followed by autumn (56%), winter (50%) and finally summer (16%) (Figure 4.14). The regression line fit to the log-transformed data (Figure 4.15) shows an increase in FS levels during the pre-BMP period followed by a decrease during the post-BMP period. A statistical comparison of the two periods indicated a significant difference (p=0.0098) between the two phases of monitoring. Analysis of the ranked data also supported this finding (p=0.0165).

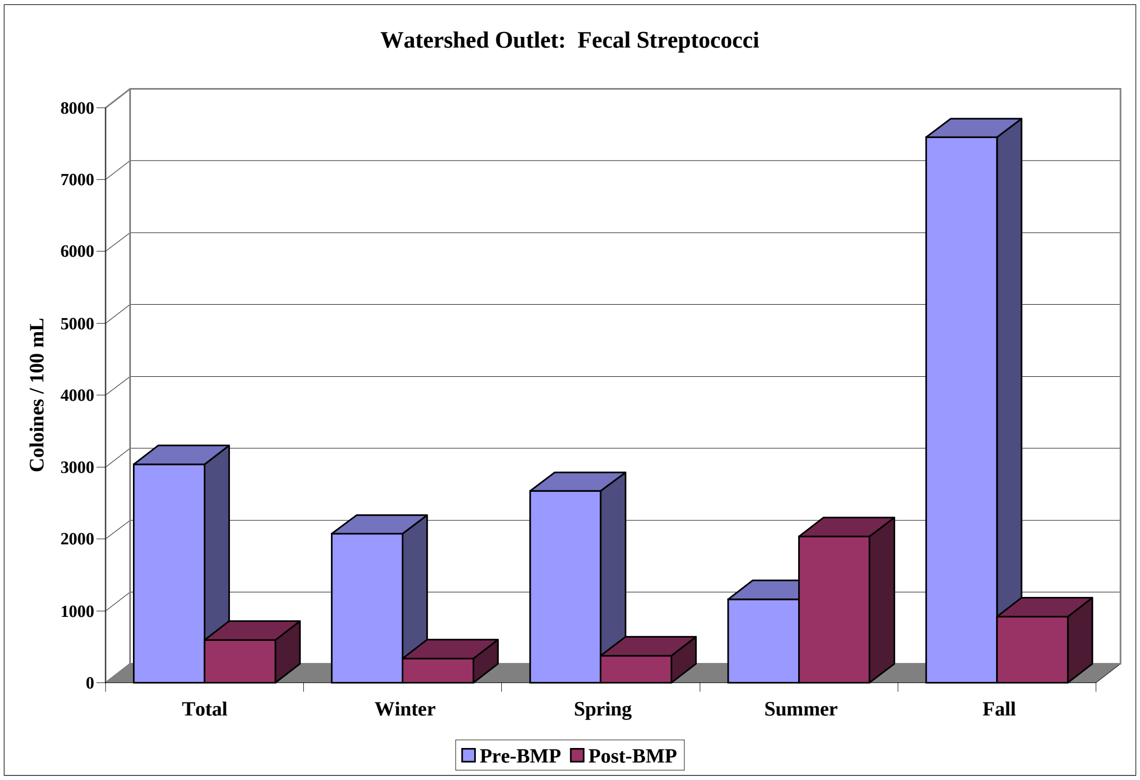


Figure 4.12 Mean fecal streptococcus bacteria at the watershed outlet

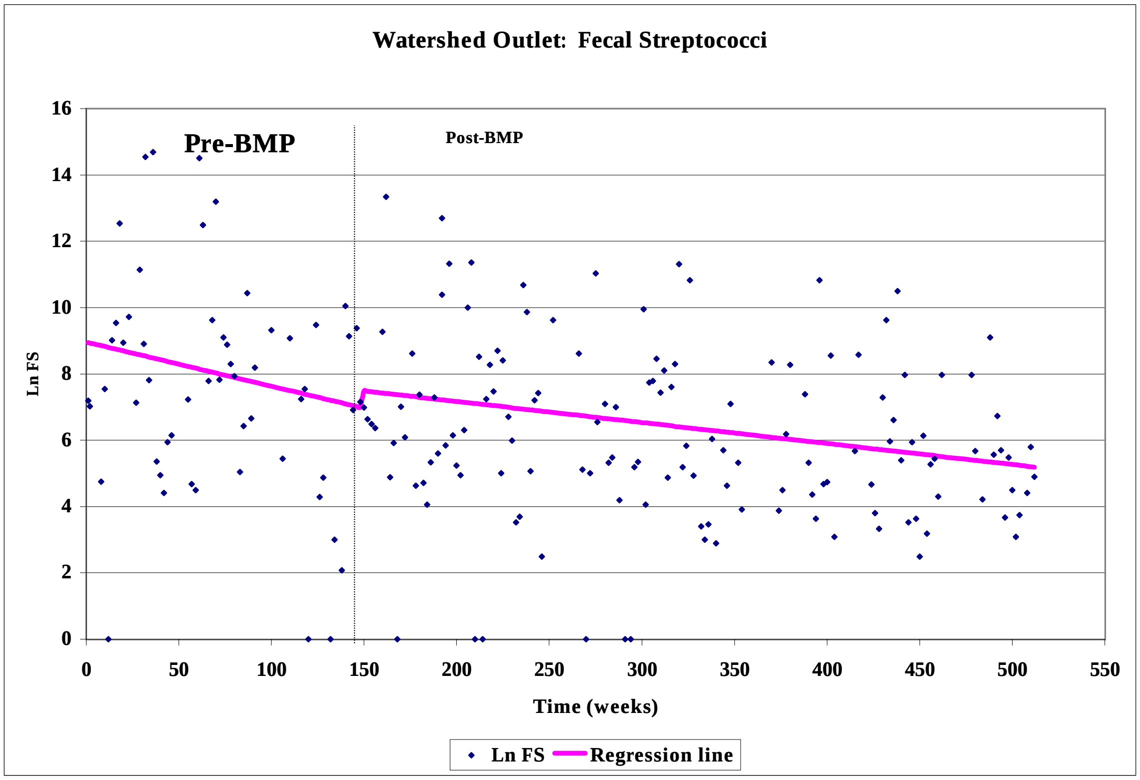
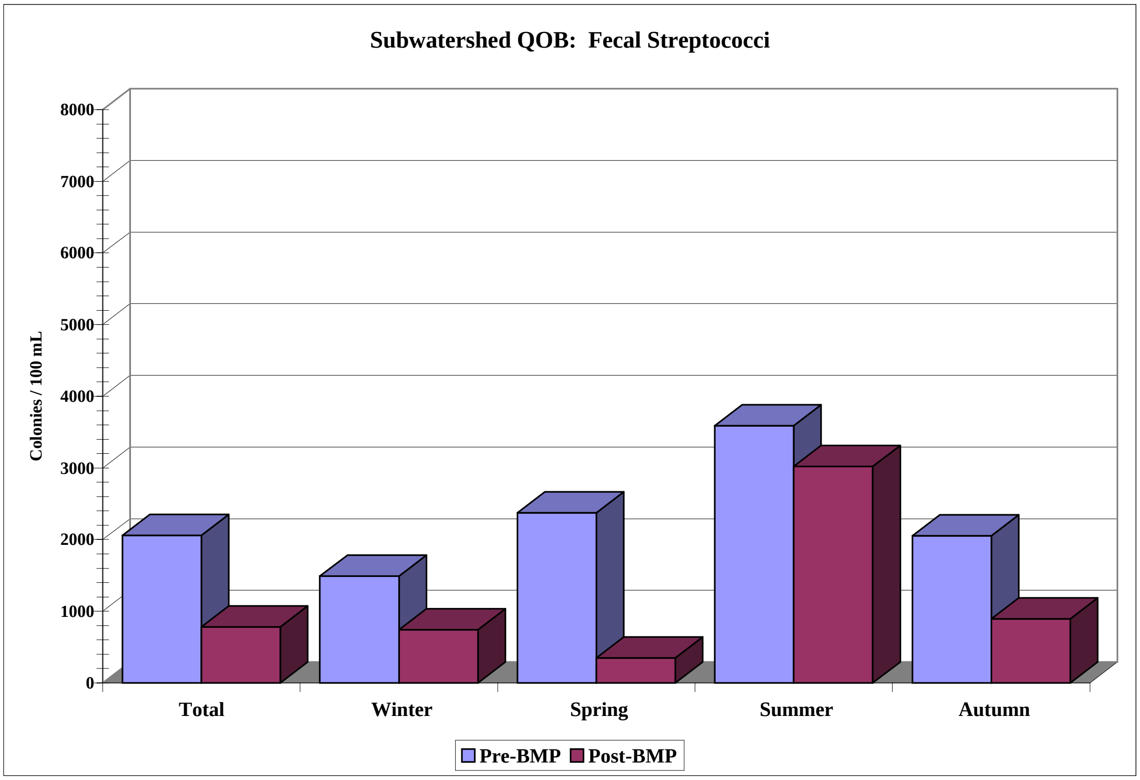


Figure 4.13 Fecal streptococcus regression at the watershed outlet


Subwatershed QOB: Fecal Streptococci
Colonies / 100 mL
8000
7000
6000
5000
4000
3000
2000
1000
0
Total
Winter
Spring
Summer
Autumn
Pre-BMP
Post-BMP

QOB

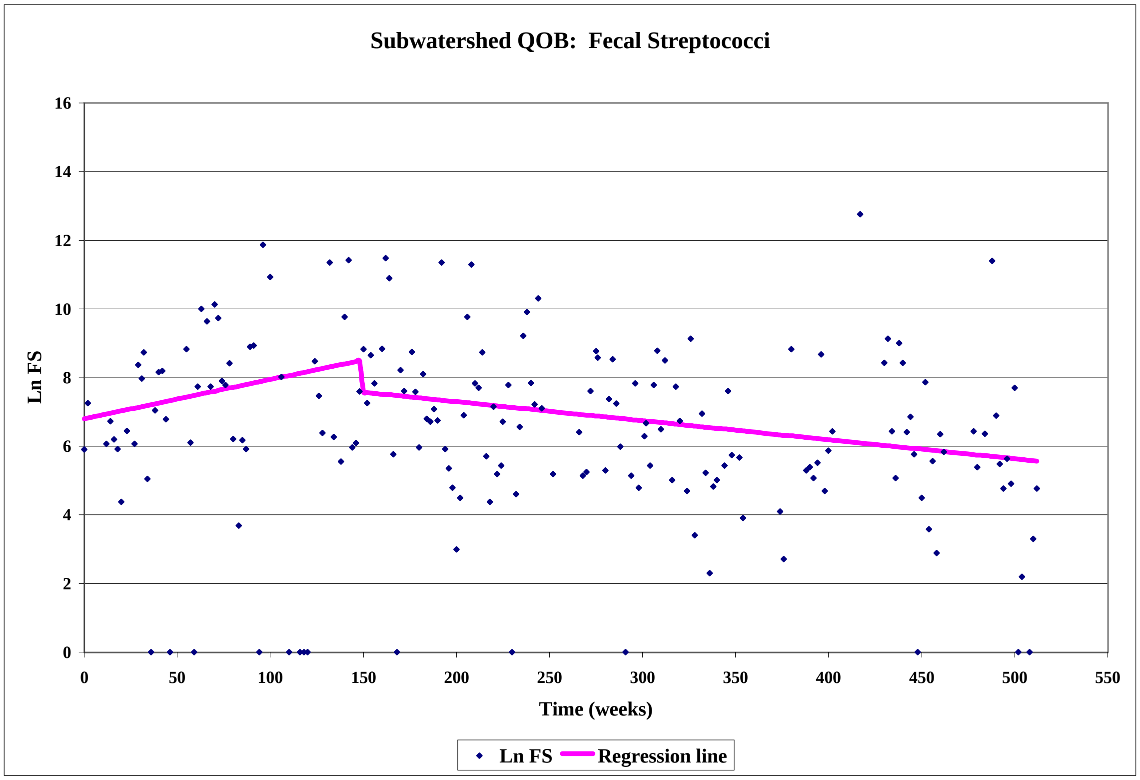


Figure 4.15 Fecal streptococcus regression of subwatershed QOB

Fecal streptococcus readings totaled 167 at station QOC—distributed between the monitoring phases as 42 pre- and 125 post-BMP. Levels of fecal streptococcus bacteria were reduced 59% at the outlet of subwatershed QOC (Figure 4.16) The greatest seasonal reductions occurred during the autumn (79%) and the spring (71%), while the winter and summer had smaller reductions of 21% and 8%, respectively. The log-transformed FS data were regressed and the pre-and post-BMP periods compared (Figure 4.17). The FS levels appear to decrease during the pre- and post-BMP phases, however, a statistical difference between the two periods was not apparent (p=0.487). The same finding held true for the regression of the ranked data (p=0.9213).

Forty-two (42) pre-BMP samples and 122 post-BMP FS samples were analyzed at the outlet of subwatershed QOD. This stations had a 69% overall reduction in fecal streptococcus levels over the course of the monitoring project (Figure 4.18). Autumn had the largest seasonal reduction at 94%, while winter and spring also had reductions in FS levels of 49% and 73%, respectively. Fecal streptococcus densities increased 350% during the summer season. Again, a lack of sufficient data available during the summer months could have impacted these results. Only two pre-BMP samples and 14 post-BMP samples were available at this site during the summer months while typically, FS seasonal data sets had 21 and 55 samples, respectively, at this subwatershed.

Regression analysis of the log-transformed data show fecal streptococcus densities decreasing during both stages of watershed monitoring at station QOD (Figure 4.19). Statistical comparison of the pre- and post-BMP data did not detect a significant difference between these two periods (p=0.487). Analysis of the ranked data provided similar results (p=0.9213).

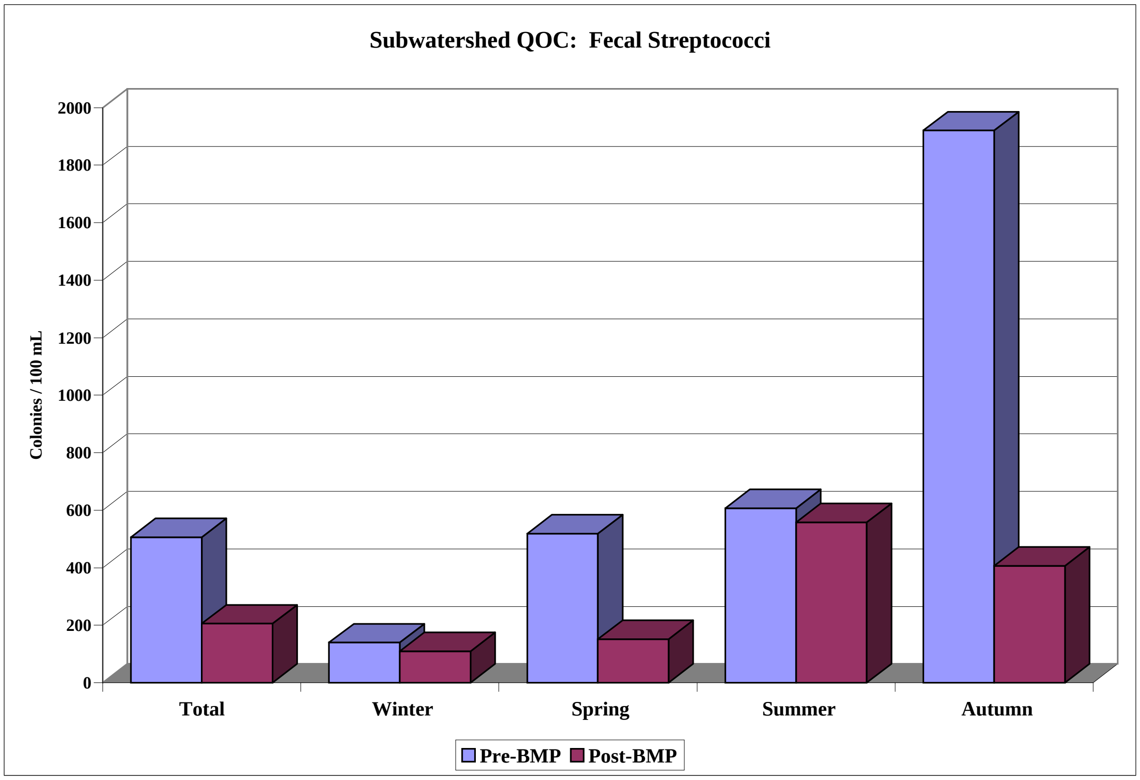


Figure 4.16 Mean fecal streptococcus bacteria from subwatershed QOD

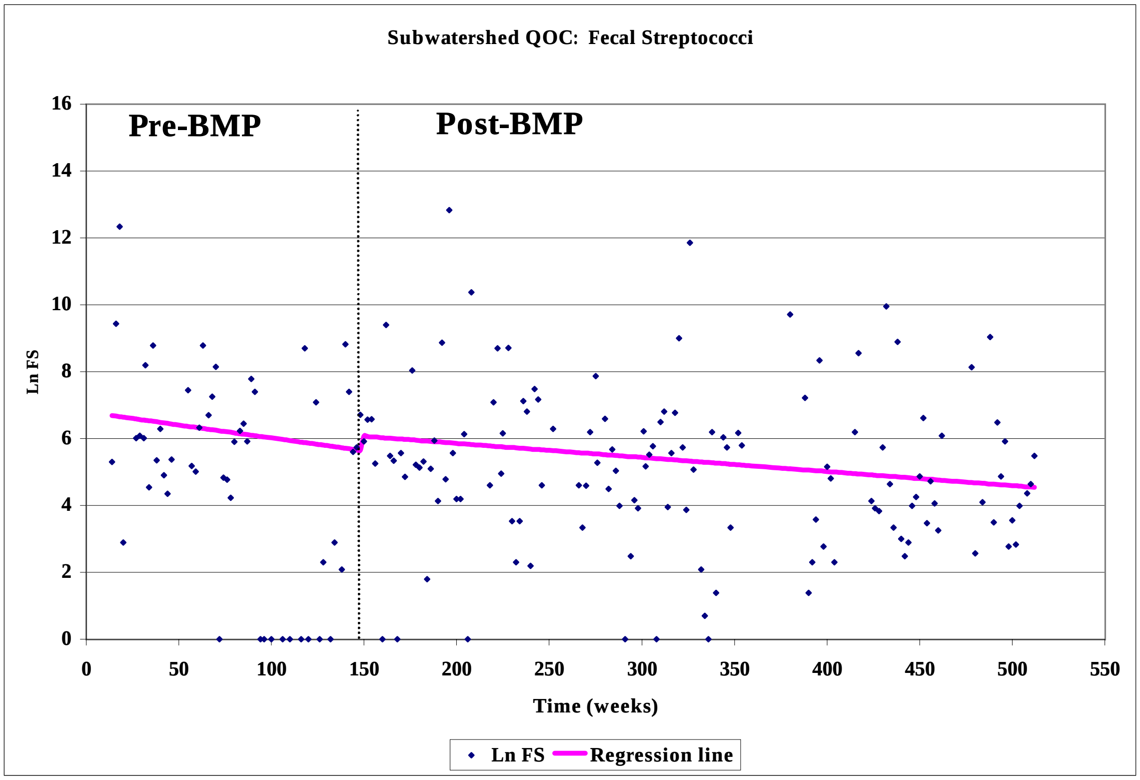


Figure 4.17 Fecal streptococcus regression of subwatershed QOC

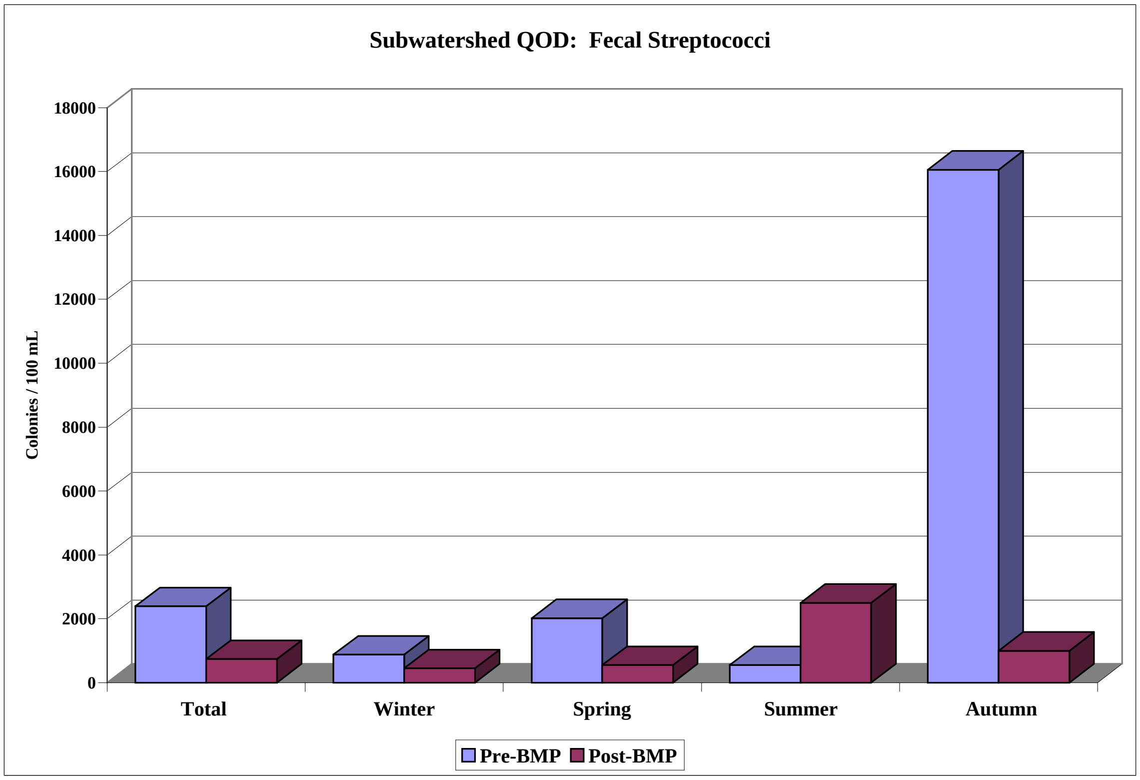


Figure 4.18 Fecal streptococcus means from subwatershed QOD

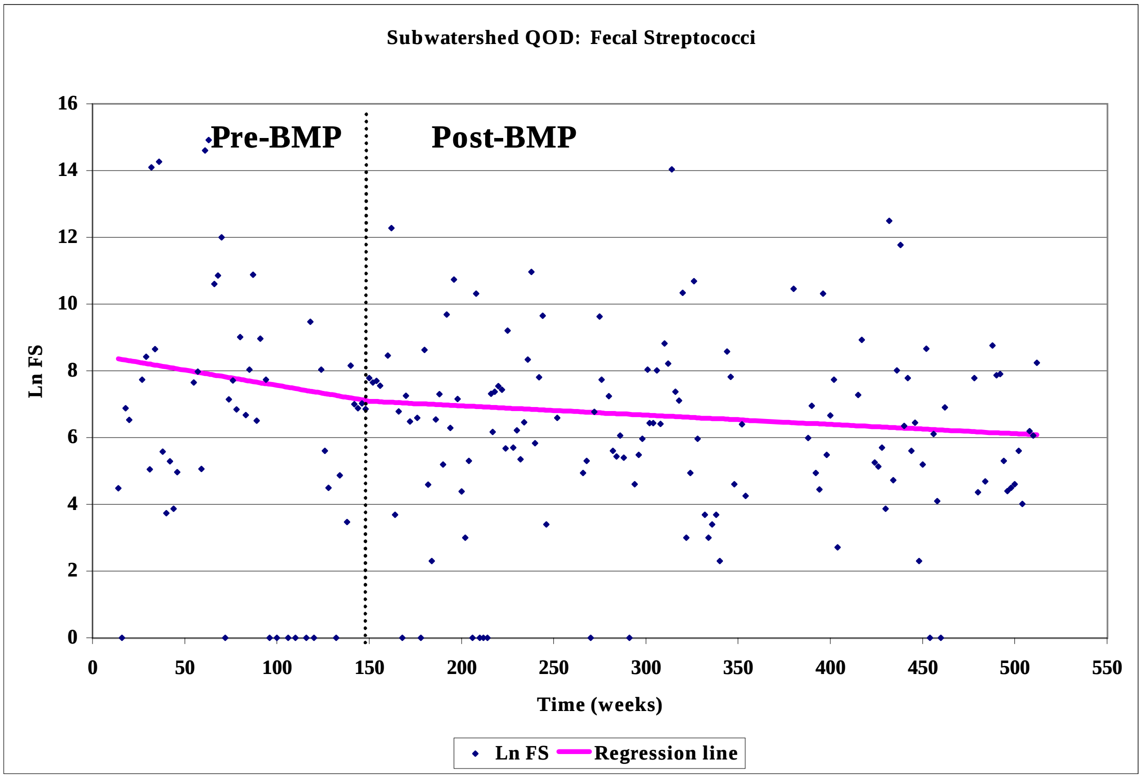


Figure 4.19 Fecal streptococcus regression of subwatershed QOD

The nonparametric trend analysis applied to the fecal streptococcus data indicated heterogeneous trends for season (p=0.000) and homogenous trends for station (p=0.972). No interaction between season and station was discovered (p=1.000). Downward trends were evident at all stations, and during the spring season at all stations. Again, it should be noted, that a lack of sufficient data during the summer and autumn seasons prohibited any seasonal trend analysis for these two periods.

The null hypothesis was rejected in favor of the alternative hypothesis, using the outcome of the Jonckheere-Terpstra test for ordered alternatives. The median fecal streptococcus levels were not equal (p=0.000) among the four monitoring stations. Similar to the fecal coliform data, the order of medians, from lowest to highest, was station C, A, B and D. The same reasoning was used here as with the fecal coliform data.

Overall fecal streptococcus levels were consistently lower at all stations during the post-BMP monitoring period. Seasonal averages typically showed a reduction in FS densities from the pre- to the post-BMP periods, with the largest reductions generally occurring in the autumn and spring months. Since precipitation and runoff were not generally proven to increase significantly over time, the large reductions observed during the autumn months further promote the theory of storing animal wastes for land application during more appropriate climatic conditions. These results again indicate that the storage of animal waste and other BMPs can aid in the reduction of microbial numbers in runoff.

Although the data indicate reductions in the FS levels at every monitoring station, only the outlet of subwatershed QOB showed statistically significant changes in fecal streptococcus measurements. This may be due to high variability in FS counts observed during the monitoring of the smaller watersheds (QOB, QOC, QOD). Other researchers (Edwards et al., 1997) have noted comparable high variability with FS data. Also, due to the high die-off rates characteristic of fecal streptococci, some researchers advise against using this bacteria as an indicator of fecal pollution because of its inaccuracy and unreliability in characterizing the presence and extent of water quality impairments (Edwards et al., 1997; APHA, 1992). The Commonwealth of Virginia does not use fecal streptococcus data when assessing the quality surface waters.

Fecal Coliform : Fecal Streptococci Ratio

The fecal coliform: fecal streptococci ratio is a parameter which has been used to determine the source of fecal pollution in waters receiving overland flow. Geldreich et. al (1968) first proposed the use of this ratio, and many researchers have reported success with this method (Doran & Linn, 1979; Doran et al., 1981; Tiedemann et al., 1988). Typically, if the ratio has a value of greater than 4, then the source of the fecal contamination is likely 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).

Fecal coliform to fecal streptococcus ratios were calculated using the data collected from the Owl Run watershed outlet and are presented in Figure 4.20. The graph suggests that throughout the monitoring study, the source of fecal pollution did not change—that domestic animals are the source of pollution during both pre- and post-BMP periods . This is not an unreasonable suggestion since the watershed is primarily agricultural and supports 5 dairy operations. Figure 4.21 depicts the FC: FS ratios from subwatershed QOB. The data presented in this graph suggest that, in general, the source of fecal pollution is typically domestic animals during the pre-BMP period and of human origin during the post-BMP period. The QOC data, presented in Figure 4.22, indicates that the pre-BMP source of pollution was non-human, typically domestic animals. During the post-BMP period, the source of fecal contamination is unclear, as the values fall between the designations of ‘human’ and ‘non-human’, although ‘domestic’ sometimes appears to be the source. During the pre-BMP period at subwatershed QOD, the source of pollution is again not clearly determined by the ratio since the values fall between the two designations (Figure 4.23). The nature of the post-BMP period fecal source is generally domestic animals, although the source is unclear during the spring season and thought to be wildlife during the autumn.

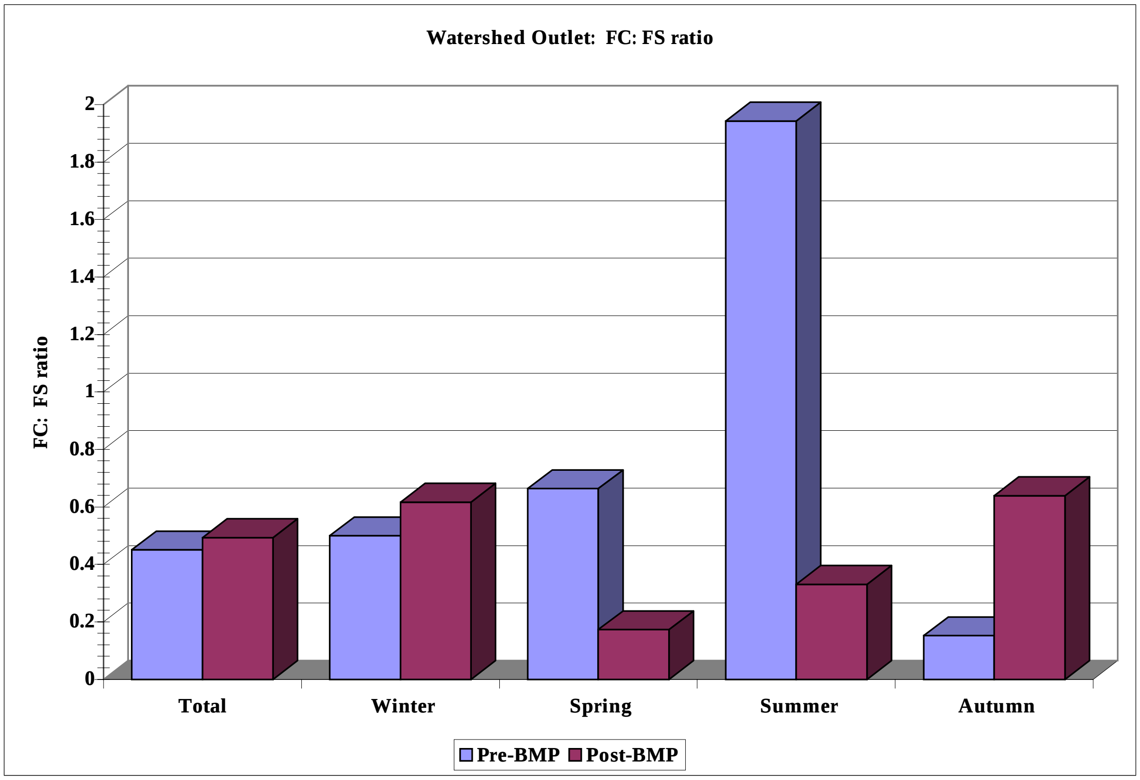


Figure 4.20 Fecal coliform : fecal streptococcus ratio at the watershed outlet

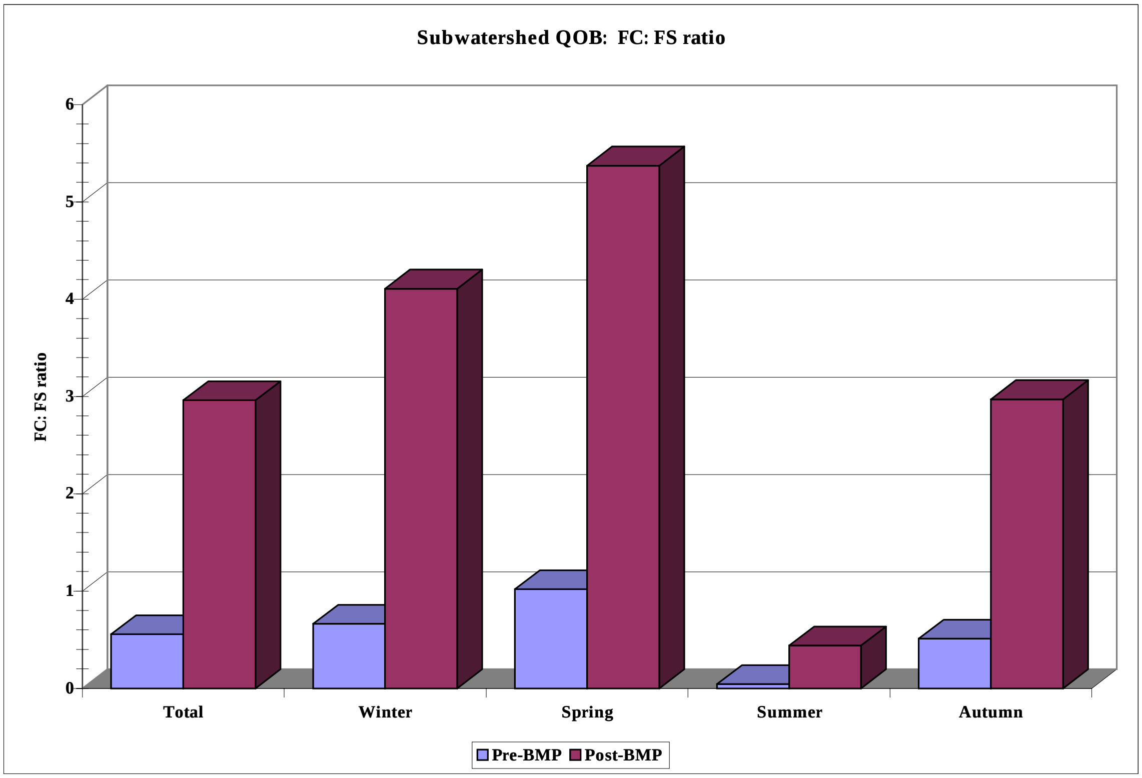


Figure 4.21 Fecal coliform : fecal streptococcus ratio from subwatershed QOB

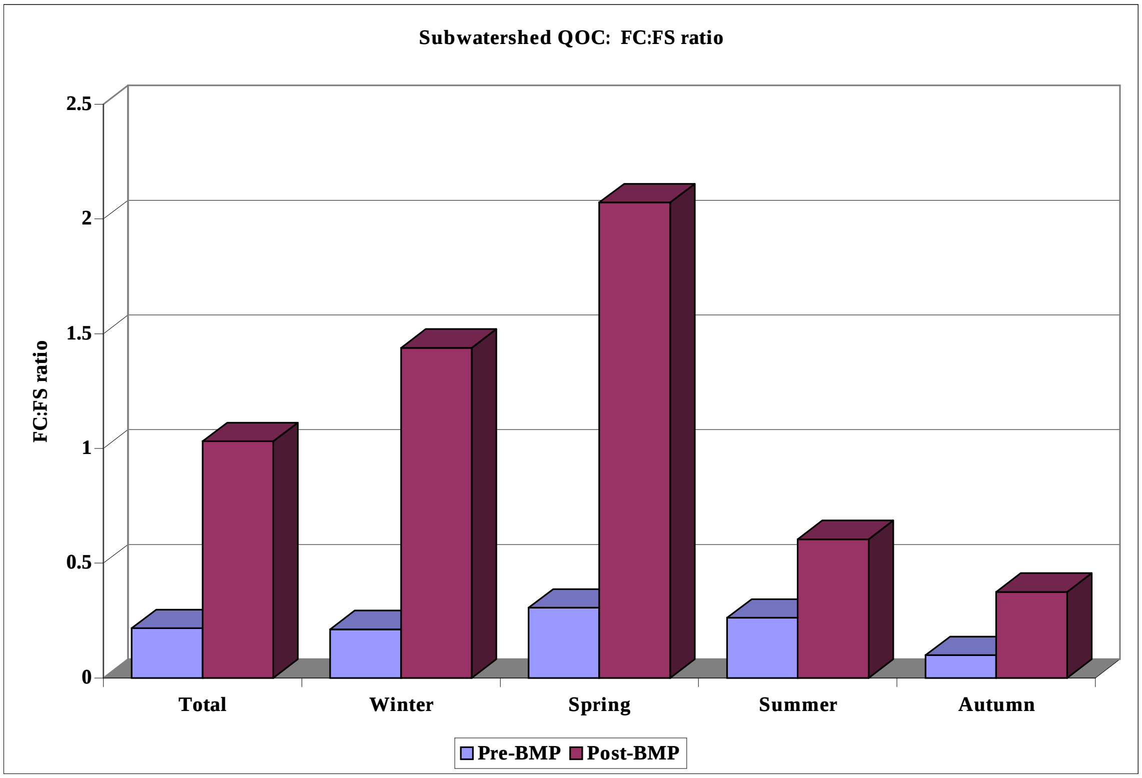


Figure 4.22 Fecal coliform : fecal streptococcus ratio from subwatershed QOC

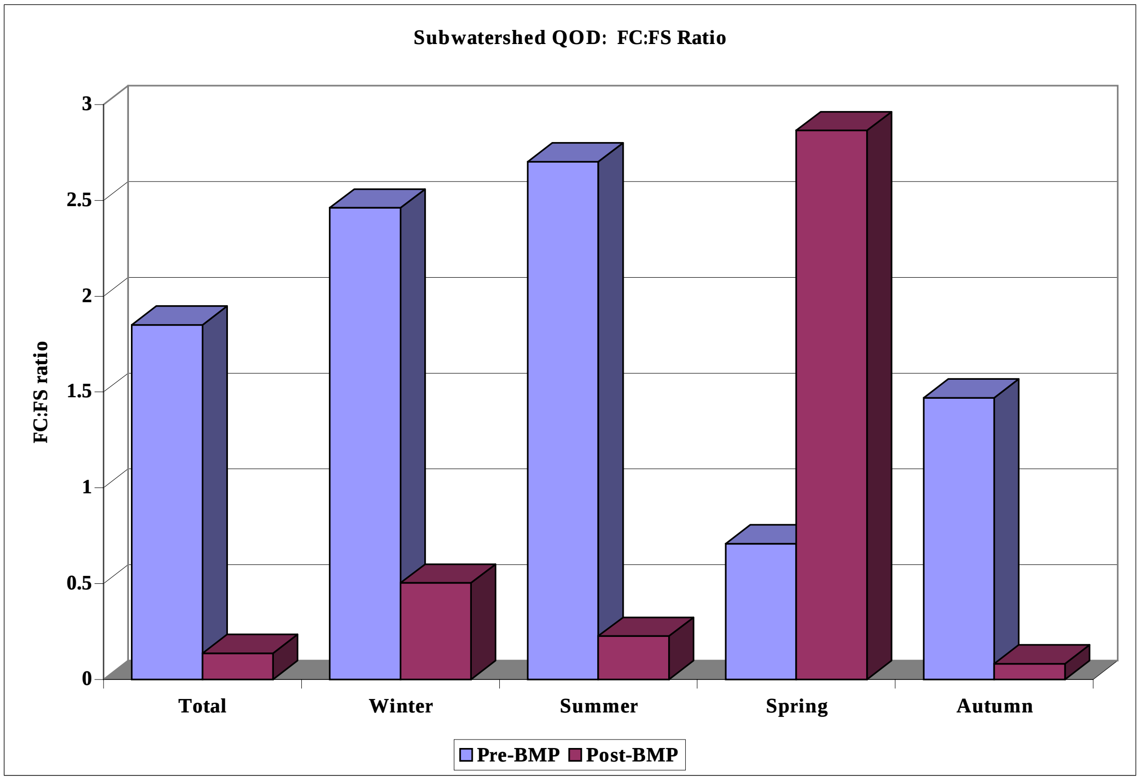


Figure 4.23 Fecal coliform : fecal streptococcus ratio from subwatershed QOD

Researchers (Edwards et al., 1997; Edwards et al., 1996) have recently found that the FC:FS ratio is not a very reliable method to correctly identify the source of fecal pollution. In a three year monitoring project of 2 northwest Arkansas streams, Edwards et al. (1997) concluded that the FC:FS ratio was not accurate in describing the source of fecal contamination within the monitored basin. The ratios calculated from the collected data suggested a human source of fecal contamination of the waters, yet there was little residential area in the vicinity. In addition, they pointed out that fecal streptococci are not reliable indicators, as non-enteric fecal streptococci are also native to insects, soil and vegetation (Edwards et al., 1997). According to APHA (1992), the varied rates of survival among streptococcus species make accurate assessments difficult. Also, the method by which fecal streptococci are enumerated can produce false-positive results (APHA, 1992). Thus, the results of this approach in determining the source of the fecal contamination should be used with caution.

Total Coliform Bacteria

From January 1988 through June 1996, bimonthly sampling for total coliform (TC) bacteria was conducted concurrently with the FC and FS data collection and analysis as a part of the biological monitoring at Owl Run. Prior to 1988, data on total coliform levels were not available. As with the FC and FS sampling, dry stream beds during the late summer and early autumn precluded the collection of water samples. Thus, a total of 122 samples were collected and analyzed for total coliform bacteria throughout the monitoring study—25 samples during the pre- BMP period and 97 samples during the post-BMP period. Laboratory analysis was conducted according to the standard methods for TC enumeration (APHA, 1992). The TC results were grouped according to season, as previously defined. Geometric means were calculated on a per season basis and used in the data analysis.

Overall, the (geometric) mean total coliform levels at the watershed outlet were reduced by 81% from the pre- to the post-BMP period (Figure 4.24). Examination of the data for each season showed the greatest reductions occurred during the summer and autumn, 89% and 93% respectively, although total coliform counts were also greatly reduced during the winter (82%) and spring (64%) seasons. The large reductions observed during the summer and autumn seasons should be viewed with caution. As mentioned earlier, the streams in Owl Run were often dry in late summer and early autumn. Therefore, often not as many surface water samples were obtained for analysis during these months as compared with the rest of the seasons. For example, during the summer season for the pre-BMP phase, only 2 water samples were obtained for total coliforms and only 14 water samples were available during the post-BMP monitoring period. Only 4 and 25 samples were available for the autumn pre- and post-BMP periods, respectively. The winter and spring seasons averaged 10 pre-BMP samples and 28 post-BMP samples. Thus, the low sample number should be considered when interpreting the total coliform data.

The distribution of the total coliform data was not normal. Regression analysis was therefore applied to the logarithmically transformed data, which were normally distributed. A downward trend was observed in the pre-BMP data, followed by a less steep post-BMP trend line (Figure

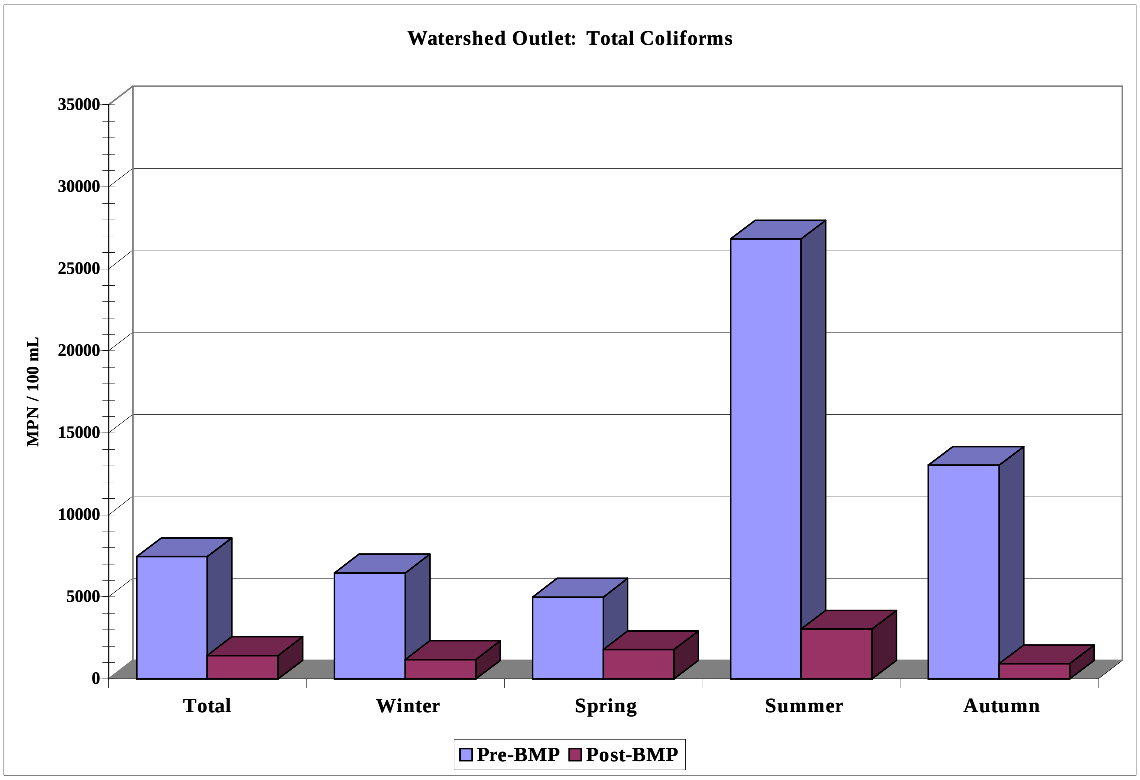


Figure 4.24 Mean total coliform bacteria at the watershed outlet

4.25). A statistical comparison of the pre- and post-BMP regression lines did not indicate a significant difference between the slopes of the two periods (p=0.0967). Similar results were obtained (p=0.1183) when regression analysis of the rank-ordered data was completed.

The total coliform data collected at the three subwatersheds of Owl Run—QOB, QOC, and QOD—were analyzed in the same manner as the main watershed outlet. Subwatershed QOB received mainly urban storm runoff from the town of Calvert. A total of 129 sample—19 pre-BMP and 110 post-BMP—were collected from QOB and analyzed for total coliform bacteria. Overall mean TC levels decreased by 42% from the pre- to the post-BMP monitoring periods (Figure 4.26). The greatest reductions per season were observed during the spring season (82%) followed by the autumn and summer seasons with 26% and 21% reductions, respectively. Total coliform levels increased by 52% during the winter season. Since the TC data were not normally distributed, a logarithmic transformation was applied. The log-transformed data were regressed, producing downward trend lines in both the pre- and post-BMP periods (Figure 4.27). A statistically significant difference between the two periods was not observed (p=0.1325). Regression of the ranked data also supported this finding (p=0.2501).

One hundred twenty four (124) water samples were analyzed for total coliform bacteria (20 pre-BMP, 114 post-BMP) at the outlet of subwatershed QOC, which was primarily agricultural with extensive cropland activities. The mean total coliform levels in this area were reduced by 36% overall from the pre- to the post-BMP period, shown in Figure 4.28. The winter and the spring seasons both had reduction of 43%, while the autumn had a 19% reduction in TC levels.

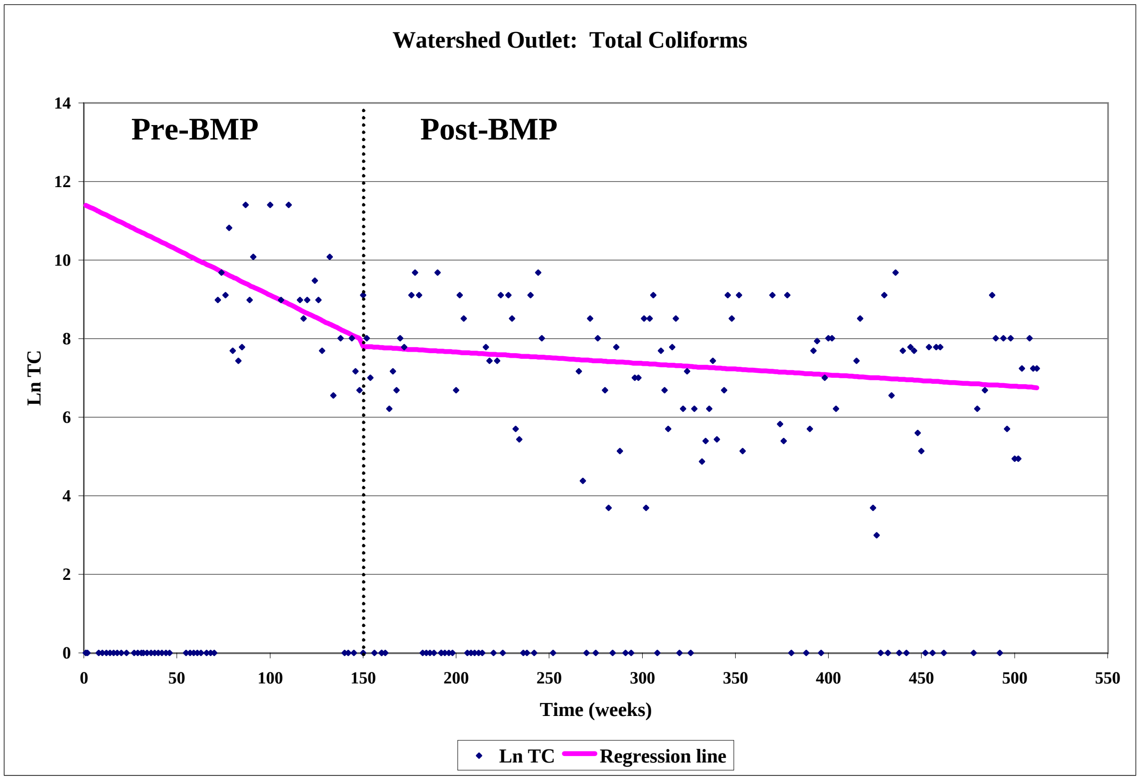


Figure 4.25 Total coliform regression at the watershed outlet

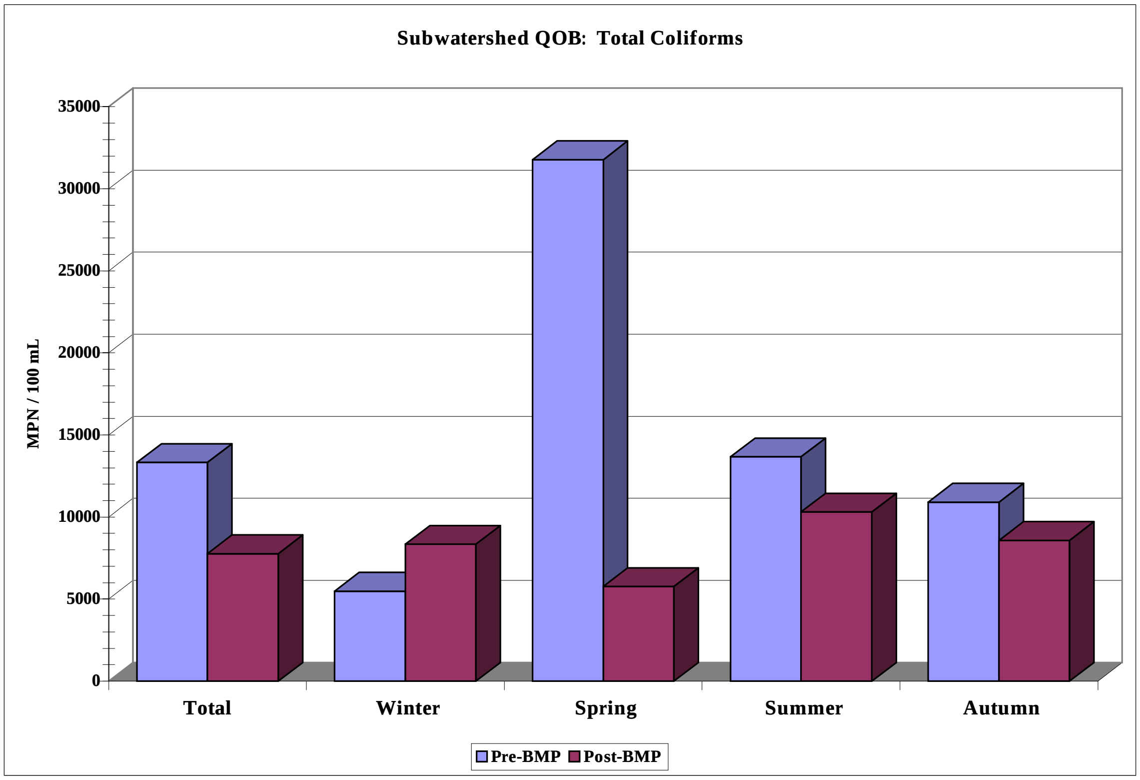


Figure 4.26 Mean total coliform bacteria from subwatershed QOB

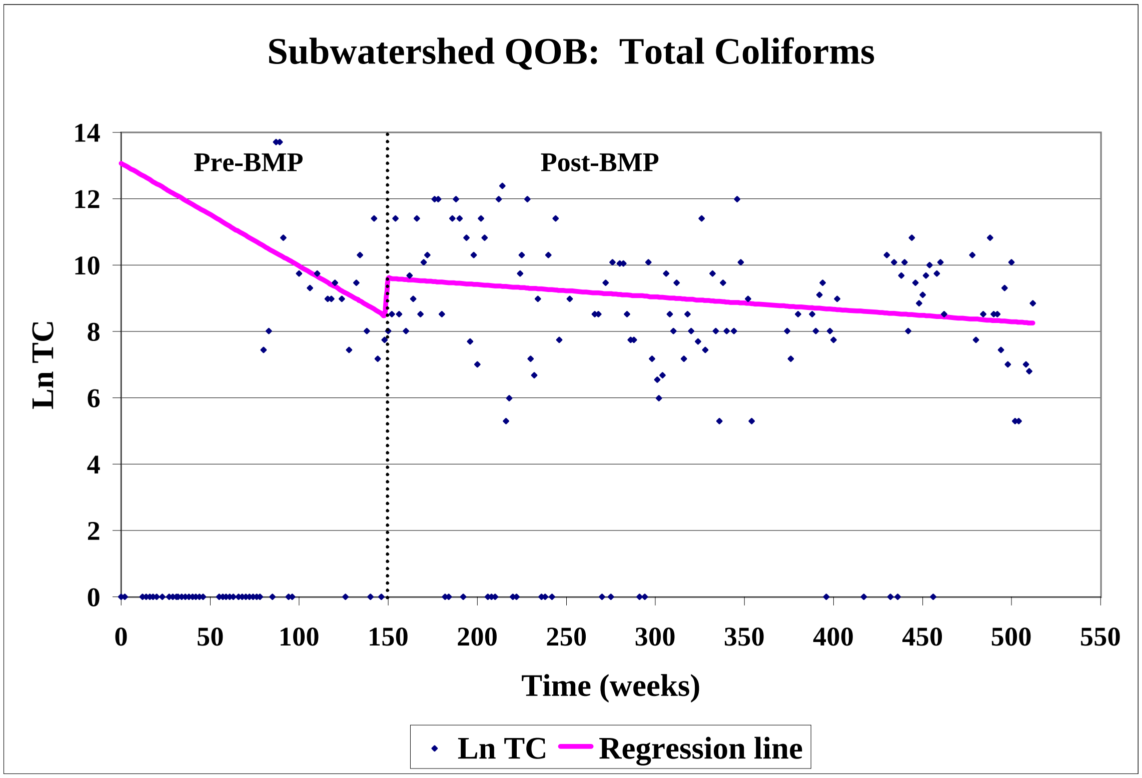


Figure 4.27 Total coliform regression of subwatershed QOB

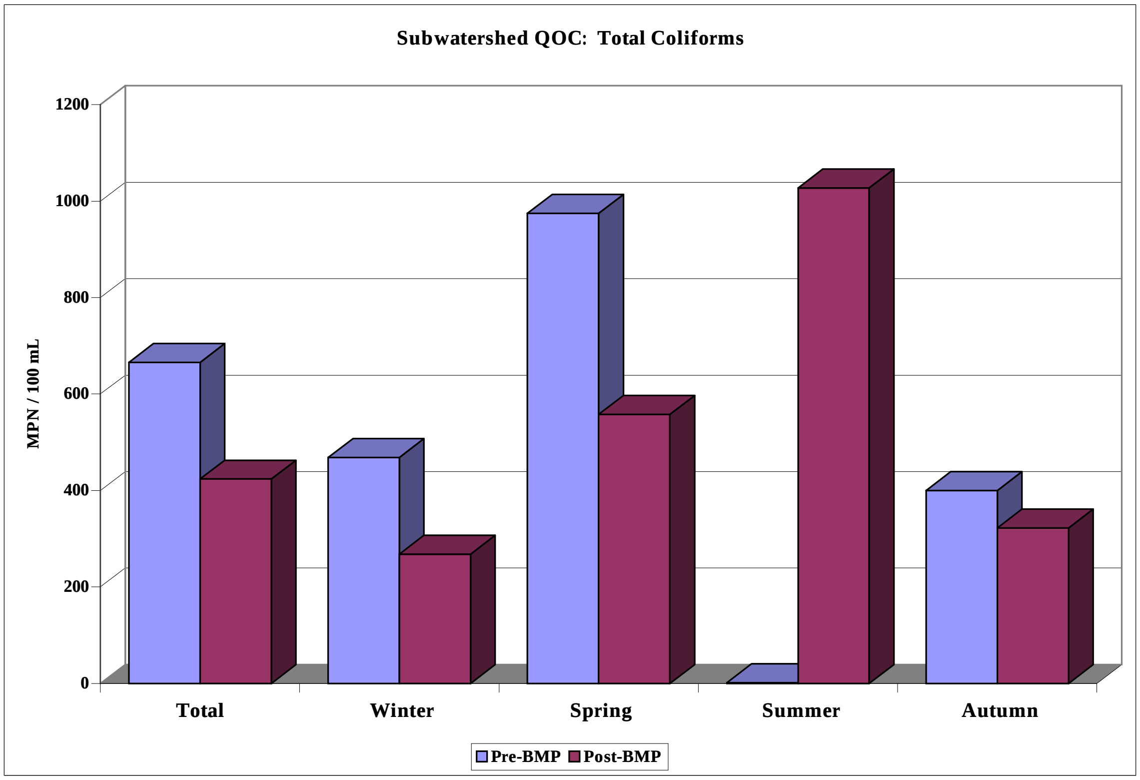


Figure 4.28 Mean total coliform bacteria from subwatershed QOD

During the summer months (June, July, and August) of the pre-BMP monitoring period, TC data were not available due to dry streambeds at this station. This lack of data during this season prevented the calculation of a seasonal mean. Neither the raw TC data, nor the log-transformed data were normally distributed. The line of best fit from the regression analysis of the log-transformed data is presented in Figure 4.29. A slight downward trend is present in the pre-BMP monitoring phase, while the post-BMP data appears to increase slightly over time. A comparison of the two lines did not result in a significant differences between the pre- and the post-BMP periods (p=0.851). Using the ranked data, similar results were obtained (p=0.569). The existence of a pond immediately upstream of site C may have masked potential impacts of any BMPs implemented in the watershed. Total coliform bacteria could have washed into the pond and remained there, undetected in the stream water samples.

Two of the five major dairy operations were located within the boundaries of subwatershed QOD. The outlet of this subwatershed was sampled 21 times for pre-BMP TC analysis and 115 times for the post-BMP. The mean total coliform levels were reduced by 28% overall at the outlet of QOD, with the greatest reductions occurring in the autumn (50%) and the winter (28%) seasons (Figure 4.30). The spring TC levels were reduced by 17%, and again, dry streams during the summer season precluded pre-BMP sampling and thus a calculation of mean total coliform densities. Neither the raw data nor the log-transformed data followed a normal distribution. Regression analysis of the log-transformed data (Figure 4.31) did not result in a significant difference between the pre-and the post-BMP periods (p=0.3329). This finding was supported by the regression analysis of the ranked data (p=0.1789)

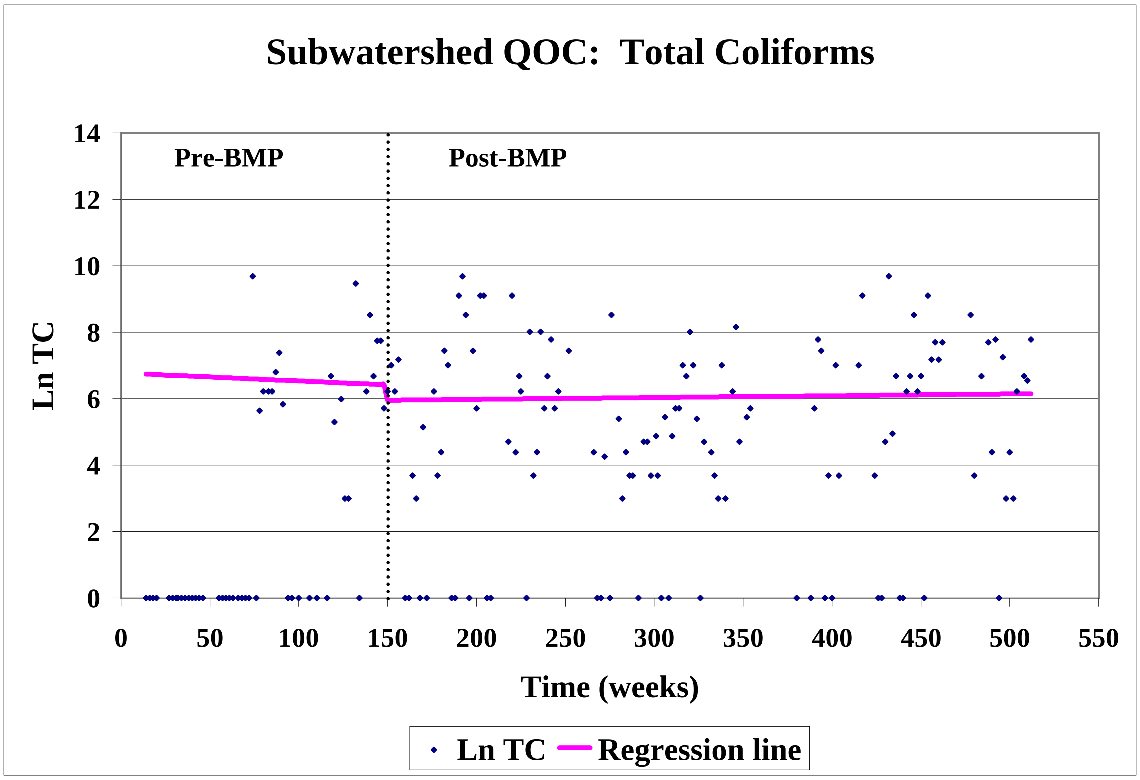


Figure 4.29 Total coliform regression of subwatershed QOC

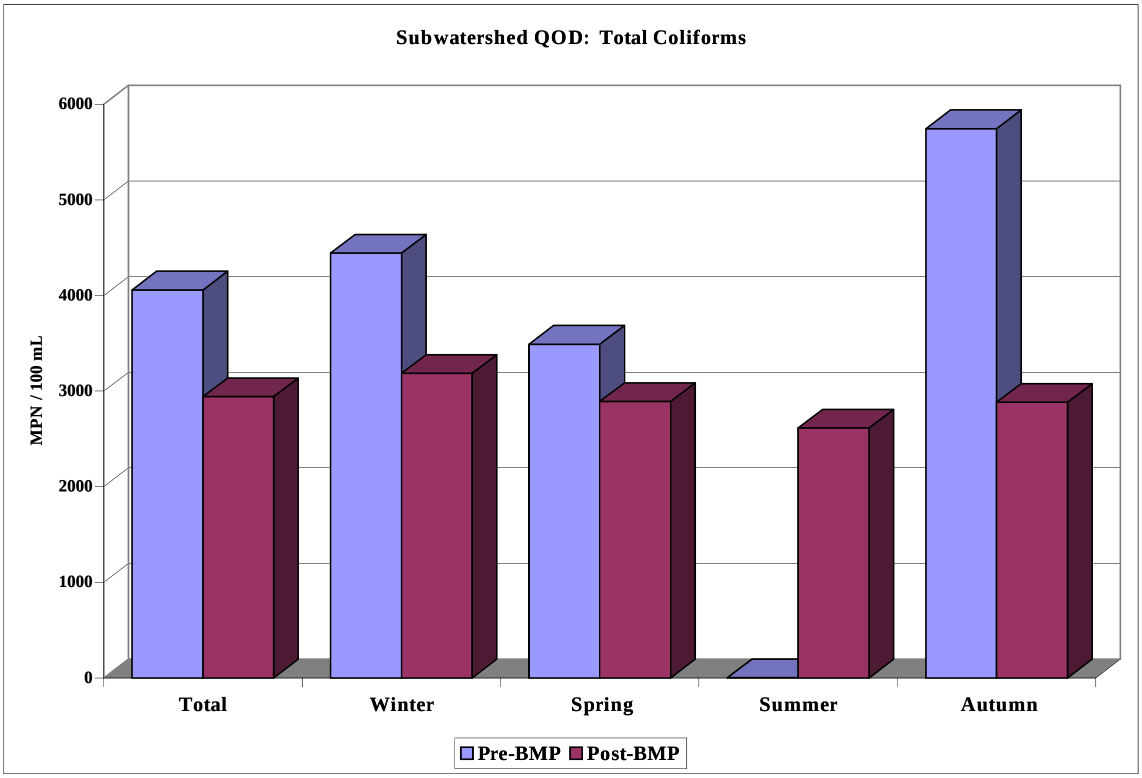


Figure 4.30 Mean total coliform bacteria from subwatershed QOD

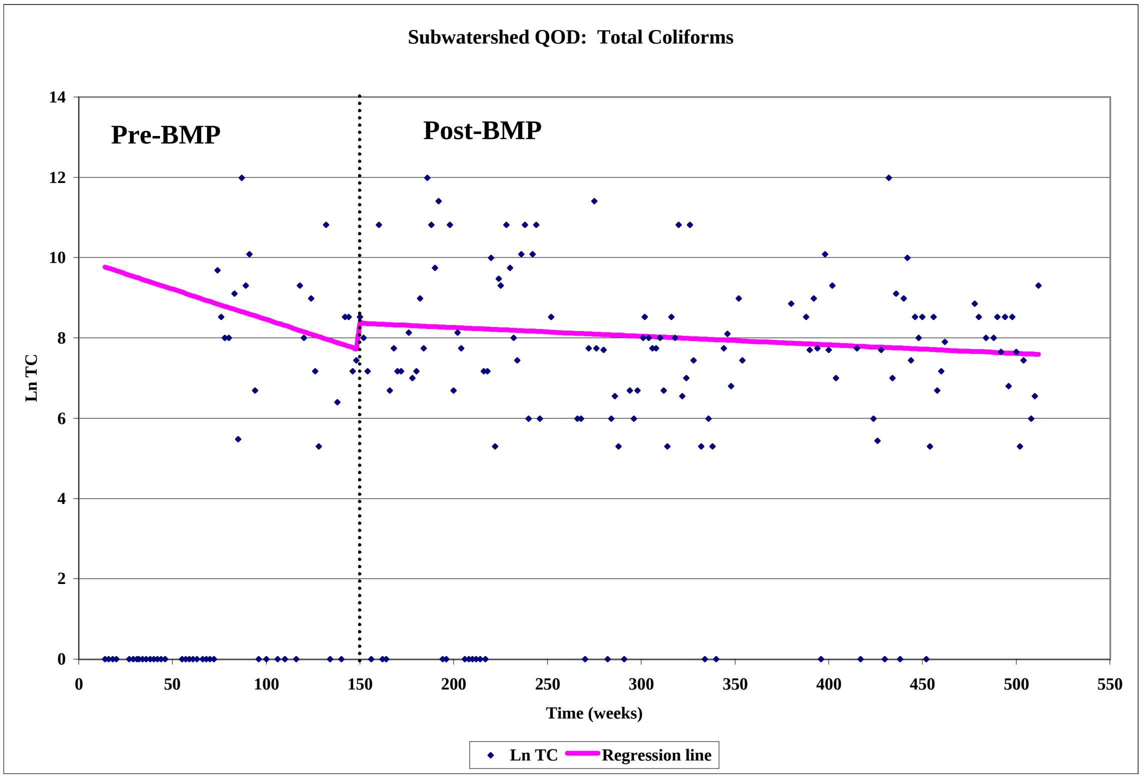


Figure 4.31 Total coliform regression of subwatershed QOD

The total coliform bacteria data were statistically analyzed to determine if any trends were present. There was little evidence to suggest heterogeneous trends among stations (p=0.568) or seasons (p=0.065). No interaction between station and season was discovered (p=0.935). Station trends were evident at the watershed outlet, station A (p=0.003), and a seasonal trend was evident during the spring season at station B. As previously noted, lack of sufficient data during the summer and autumn seasons prohibited any seasonal trend analysis for these two periods.

The median total coliform levels were compared among the surface monitoring stations using the Jonckheere-Terpstra test for ordered alternatives. The results of this comparison proved the median bacteria levels unequal among the stations (p=0.000). The order of medians, from lowest to highest, was station C, D, B and A, using the same reasoning as with the other bacteriological data.

The greatest overall percent reduction in the (geometric) mean total coliform bacteria occurred at the watershed outlet, station QOA. Subwatershed QOB had the second largest reduction in TC levels, followed by QOC and QOD. Station QOB generally had the highest seasonal levels of total coliforms, followed by QOA and QOD, while TC levels were consistently the lowest each season at the outlet of subwatershed QOC. The reductions in TC levels at station D are important to note. Two intense livestock operations were functional within QOD, and two animal waste storage structures, along with the additional BMPs which were installed throughout this subwatershed as a component of the investigation. The overall reductions in TC densities from the pre- to the post-BMP periods suggest that the adoption of such practices contributes to the reduction of the bacterial pollutants associated with animal waste conveyed via storm water runoff. The low values of TC bacteria observed at the outlet of subwatershed QOC were anticipated as the land use in this area is primarily cropland rather than livestock operations, and is not as heavily influenced by livestock presence. Also, the sizable pond likely influenced the bacteria levels by serving as a detention area for the coliform bacteria.

Although nearly all stations had seasonal reductions from the pre- to the post-BMP period, no season consistently had greater reductions than another. This is somewhat unexpected since the installation of the manure holding facilities provided for storage of the material over the winter months, thus no manure was generally land-applied post-BMP. Therefore, the greatest reductions would have been expected during the winter and autumn months, which was not always the case.

All the regression lines of the log-transformed total coliform data had a negative slope during the pre-BMP period. With the exception of the very slight increase in slope seen at station QOC, the post-BMP regression line followed the same pattern as the pre-BMP data. Statistical comparison of the pre- and post-BMP data did not provide evidence of a significant difference between the two monitoring periods at any station. This finding was supported by the results of both the regression analyses. One should note that total coliform data were not available until 1.5 years into the monitoring project, thus the post-BMP period contained considerably more TC data than the pre-BMP period. Had more pre-BMP data been available, perhaps the results of the statistical analysis would have been different.

Trend detection techniques were applied to the total coliform data. The results of this analysis provided little evidence for the presence of any trends among the data. As noted previously, this could be due to an insufficient amount of data. The comparison among median total coliform levels indicates that the lowest levels of total coliform bacteria were at station C, followed by station A, B and D.

There is evidence that the BMPs were generally successful in reducing the amount of total coliforms present at the watershed outlet. Precipitation and runoff amounts did not increase during the monitoring period. The results of the total coliform analysis show large reductions from the pre- to the post-BMP period in both the overall and seasonal data. Reductions in the amount of total coliforms leaving the Owl Run watershed were expected due to the combination of structural and managerial BMPs which were implemented as part of the research. Because of the waste storage provided by the installed holding tanks, less manure was land applied during the colder months and/or inclement weather. Thus, the greatest reduction would have been expected during the winter and autumn, which was not the case. Total coliform bacteria, however, are not unique to the intestines of warm-blooded animals. They are present throughout nature, and these other sources of TC bacteria may have contributed to the results. The statistical analysis did not suggest a significant difference between the monitoring periods, although a lack of data could have impacted the outcome of the analysis.

Total coliform bacteria are considered a type of indicator bacteria, acting as a signal that fecal pollution of waters has occurred. One should note, however, that Virginia surface water quality standards are not based on total coliform numbers but solely on fecal coliform bacteria levels (SWCB, 1992). The Commonwealth uses total coliform bacteria in the assessment of drinking water quality and has TC drinking water standards which water authorities are required to meet

(DEQ, 1998). Waterworks within the Commonwealth of Virginia test for the presence or absence of total coliforms in a water sample, rather than a coliform density (as is the result of the MPN enumeration technique). Water authorities are required to collect and test monthly samples of their water. A water authority which is required to collect at least 40 samples within a month is in compliance with the primary maximum contaminant levels (PMCLs) if not more than 5.0% of the samples collected test positive for total coliforms. An authority which is required to collect less than 40 samples per month must not exceed one (1) positive total coliform in order to remain in compliance with the PMCLs (DEQ, 1998)

Summary

Bacteriological data are known to be difficult to analyze. The bacteriological data collected from the Owl Run watershed had a six-fold magnitude range of values. None of the bacteriological data sets had a normal distribution, while there was evidence that roughly half of the logarithmically transformed data sets were normally distributed. The tremendous amount of variability made for a challenging data analysis. Geometric means were used to examine average bacteria values. Overall reductions in fecal coliform, fecal streptococcus, and total coliform levels were seen at the watershed outlet and subwatershed monitoring stations (with the exception of the fecal coliform data which increased at the subwatersheds). Examination of average fecal bacteria levels can provide a general overview of what is occurring, however to describe such a complex phenomena as bacterial presence in surface waters with a single value can possibly misleading. Therefore, statistical analysis techniques were applied to the data. This method of analysis was not without problems either. Parametric statistical tests (regression analyses) are powerful, but require the data to be normally distributed. Due to the split between normal and non-normally distributed data, nonparametric tests (trend analysis) were also used. Using all these methods of evaluation, the impact of the BMP adoption on the surface waters was completed. Since multiple methods of analysis were employed, the average reductions and statistically different regression lines and trend detections all work together to support BMP implementation as a means of improving the bacteriological quality of surface waters. The bacteriological data collected and analyzed show reductions occurring in fecal coliform and fecal streptococcus, and total coliform levels over the course of the monitoring study. This, coupled with the results of the statistical analysis, suggest that the BMPs which were implemented in the Owl Run watershed were effective in reducing the amount of enteric microbes entering the surface water, and thus improving the quality of such receiving waters. More specifically, the animal waste storage facilities—the majority of which were constructed as a part of this project—appear to be quite effective in reducing such pollutants. The storage of such waste material provides microbial die-off by creating a hostile environment for the microorganism survival while also allowing a more planned application of the waste to the receiving fields. In general, during the post-BMP period, greater reductions were observed during the cooler months, when the animal waste was stored rather than land applied on a regular basis, as was the practice prior to BMP installation.

Summary and Conclusions

The Owl Run watershed, located in Fauquier County, Virginia, was monitored over a period of ten years, beginning in 1986. After the first 2 ½ years of extensive pre-BMP monitoring, a variety of Best Management Practices (BMPs) were installed throughout the watershed, and monitoring continued. The BMP program was designed to target better management and utilization of animal waste, although other BMPs, including conservation tillage, field strip cropping, grassed waterways and alternate livestock water sources, were also implemented in conjunction with the investigation. The specific goal of this study was to evaluate the bacteriological quality of surface water in order to assess the impact of the BMPs implemented within the Owl Run watershed.

Landuse within the watershed was primarily agricultural, including 5 dairy operations as well as cropping activities. The field data collected from the watershed included precipitation in terms of quantity, quality and intensity, evaporation, wind speed and direction, solar radiation, air temperature, and relative humidity (Mostaghimi et al., 1989). Automatic water quality samples were used to collect discrete runoff samples for chemical analysis. Stage recorders and data loggers measured the quantity and rate of runoff (Mostaghimi et al., 1989). Surface water grab samples were collected on a bimonthly basis and analyzed for fecal coliform, fecal streptococcus, and total coliform bacteria according to standard methods (APHA, 1982, 1985, 1995). Biological monitoring also included quarterly sampling conducted for substrate colonization of algae, protozoan, and related microorganisms. Land use records were collected twice per year and stored and analyzed using an internally developed geographic information systems software program.

Both precipitation and runoff data were stored within the HAS (Carr et al., 1988) data management system. Daily precipitation and runoff values were calculated by applying the THEISSAN and TOTALS programs, within the HAS management system. Monthly values for both parameters were used in further data analysis. Geometric means were used to represent average bacteriological levels. Seasonal averages were calculated based on four, three-month seasons.

The data were analyzed using a combination of statistical techniques. Because of the nearly equal spilt of normal and nonnormal distributions among the bacteriological data, both parametric and nonparametric analyses were employed. Stepwise multiple linear regression analysis was used to detect monotonic trends in the bacteriological data. Nonparametric trend analyses tests were also applied to the data. Finally, a comparison among monitoring stations of the various bacteriological levels was performed. The results of the data analyses suggest the following:

1) The average rainfall amount in the Owl Run watershed increased 3% from the pre- to the post-BMP monitoring periods, however, statistical analysis indicated no significant difference in rainfall quantity between the two periods. It could be concluded that the quantity of precipitation remained relatively constant over the study period and therefore did not significantly contribute to changes in the bacteriological surface water quality.

2) Monthly runoff totals increased 39% from the pre- to the post-BMP periods at the watershed outlet. Increases at all of the subwatershed outlets occurred as well (B, 40%; C, 38%; D, 16%). Statistical analysis did not show a significant difference in runoff between the two monitoring periods, except at station C where post-BMP runoff was significantly greater than the values measured during the pre-BMP period. Other than at station C, runoff totals were similar during both phases of monitoring. Although BMP implementation did not specifically target watershed hydrology, the runoff would not be expected to increase over time, as there was not an appreciable increase in precipitation. Differences in rainfall pattern and distribution, however, may partially explain the increased runoff volume during the post-BMP period.

3) The amount of land under cropland production increased by 11% from the pre- to the post-BMP period. Pasture land experienced a 27% increase. The increasing trends in both categories were statistically significant, using trend analysis techniques. Fertilizer records showed a decrease in the overall rate of manure application and total nutrient loadings from the pre- to the post-BMP period. Maximum and minimum manure application rates occurred during 1987 and 1995, respectively. Within subwatersheds QOC and QOD, there was an

increase in the rate of manure application and nutrient loadings from the pre- to the post-BMP period.

4) Fecal coliform bacteria at the watershed outlet decreased by 40% from the pre- to the post-BMP period. However, the subwatershed monitoring stations all indicated increases in overall fecal coliform levels (B, 103%; C, 94%; D, 9%). The seasonal means at the watershed outlet were consistently lower during the post-BMP period for all four seasons. The post-BMP seasonal means at the outlet of the subwatersheds were consistently greater than the pre-BMP period during the winter and summer, while there were mixed responses (i.e. both increases and decreases) during the spring and autumn seasons at these stations. Regression analysis of the fecal coliform data showed a statistically significant difference between the pre- and the post-BMP periods. Similar statistical results were obtained for all subwatersheds. No trends were found among any of the fecal coliform data.

5) The Commonwealth of Virginia has two surface water quality standards (other than shellfish waters) for fecal coliform bacteria. The percent of violations of the first standard, not to exceed a geometric mean of 200 / 100 mL within 30 days, was reduced by 13% at the watershed outlet during the post-BMP period, as compared to the pre-BMP phase. The subwatershed monitoring stations all experienced increases in the percentage of violations during the post-BMP period (B, 16%; C, 10%; D, 31%). The second standard, not to exceed a fecal coliform count of 1000 / mL at any time, had a 7% reduction in violations from the pre- to the post-BMP period. Station D had a 2% reduction in the percent of violations, while stations B and C had 5% and 14% increases in the percentage of violations, respectively.

6) Fecal streptococcus bacteria were reduced by 80% at the watershed outlet. The corresponding reductions for the B, C and D subwatersheds were 62%, 59%, and 69%, respectively. Seasonal reductions in fecal streptococcus bacteria occurred during all seasons at the watershed outlet, from 84% to 88%, except during the summer for which the levels of FS bacteria increased by 25%. The subwatershed stations all showed seasonal reductions in FS levels, ranging from 8% to 94% during the post-BMP phase, with the exception of the summer season at station D. The summer season fecal streptococcus levels at this station increased by 350% from the pre- to the post-BMP phase. A statistically significant difference between the pre- and the post-BMP fecal streptococcus data was found only at station B using regression analysis techniques. Individual monitoring stations were found to have downward FS water quality trends and exhibited seasonal trends during the spring. A great amount of variability was observed in the fecal streptococcus data, as has been reported by others investigators. Due to the rapid die-off rate of fecal streptococci, coupled with this high variability, fecal streptococcus bacteria are not reliable indicators of fecal contamination, and are not used in evaluating surface water quality in the Commonwealth of Virginia.

7) The ratio of the fecal coliform to fecal streptococcus bacteria (FC:FS) is a method used to resolve the source of fecal contamination based on the proportion of the fecal bacteria. A ratio of less than 0.1 indicates wildlife, 0.1 to 0.6 indicates domestic animals, and greater than 4.0 indicates human waste as a possible contamination source. This method was applied to the Owl Run watershed. Both the pre- and the post-BMP phases had ratios (0.45 and 0.49, respectively) indicating domestic animals as the principal originator of the fecal pollution. The calculation of seasonal FC: FS ratios at the watershed outlet also indicated domestic animals

as the source of the fecal contamination for all seasons. Fecal contamination at subwatershed B moved from domestic animals during the pre-BMP (0.56) to an undetermined source during the post-BMP period (2.96). Seasonal FC:FS ratios followed the same pattern. Station C also moved from domestic animals during the pre-BMP (0.22) to an undetermined source of pollution for the post-BMP (1.03). Similar results were found using the seasonal data. The source of fecal pollution at station D was unclear during the pre- BMP period (1.85) and for the post-BMP period the ratio (0.14) indicated that domestic animals were the primary source. Seasonal calculations indicated likewise. Domestic animals were often cited as the source of the fecal contamination of the surface waters. This is not an unreasonable suggestion, as the watershed landuse is over 70% agricultural, including 5 major dairy operations. Although for numerous reasons, the FC: FS ratio is not endorsed by the APHA as a sound method for determining the source of fecal contamination.

8) An overall reduction of 81% was observed in the total coliform concentration at the watershed outlet from the pre- to the post-BMP periods. Seasonal reductions ranging from 64% to 93% occurred during each season. Stations B, C, and D also showed overall reductions in TC levels: 42%, 36% and 28%, respectively. Seasonal reductions at station B occurred during the spring (82%), summer (21%) and autumn (26%), while the winter season experienced a 52% increase. At station C, reductions in TC levels occurred during winter (43%), spring (43%) and autumn (19%). Due to dry streambeds, a seasonal calculation of the summer total coliform levels at station C was not possible. Station D had reductions during the winter (28%), spring (17%) and autumn (50%). Again, dry streams during the summer prevented a seasonal calculation at this station. Regression analyses of the total coliform

bacteria did not show a significant difference between the pre- and the post-BMP periods, at the watershed outlet or at any of the subwatersheds. Individual station trends were evident at the watershed outlet, station A, and the spring season showed a seasonal trend at station B. Likely, the results concerning the total coliform data were influenced by the small amount of pre-BMP data collected. Had more pre-BMP data been available, the results of the statistical analyses could have been different.

9) The median fecal bacteria levels (of all bacteriological parameters tested) were not equal among the four monitoring stations. At least one strict inequality existed within the expression: $C \leq A \leq B \leq D$. These results were attributed to the sizable pond above the QOC station, and the two dairy operations within QOD. Dilution likely influenced fecal bacteria concentrations at the watershed outlet.

10) The reductions in bacteria levels during the cooler seasons suggest that the storage of animal wastes, in addition to the flexibility in the timing of land application, aid in the reduction of bacteriological levels in runoff. Increases in fecal bacteria during the spring and autumn are likely related to the intensive land application of animal wastes that occurred during these seasons, post-BMP.

An increased amount of animal waste management occurred in conjunction with the monitoring project. The analysis of the pre- and the post-BMP data suggest that the adoption of BMPs can improve water quality by decreasing the levels of fecal bacteria associated with animal waste as well as those conveyed to receiving waters via overland flow.

Suggestions for Future Research

The comprehensive monitoring of the Owl Run watershed produced one of the largest databases to date concerning nonpoint source pollution. One suggestion for future study would involve using this data to improve upon the already existing computer simulation models to include a bacteriological component, or develop new models which could better describe the bacteriological contributions of NPS pollution. For future watershed studies, if perennial streams could be sampled, rather than intermittent streams, one could avoid a situation of an incomplete data set. Finally, if sizeable ponds, lakes reservoirs, etc. are present within a watershed being monitored, include upstream-downstream monitoring of these sites, as they could possibly mask BMP impact on water quality.

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Appendix A

Monthly runoff totals at the subwatershed monitoring stations

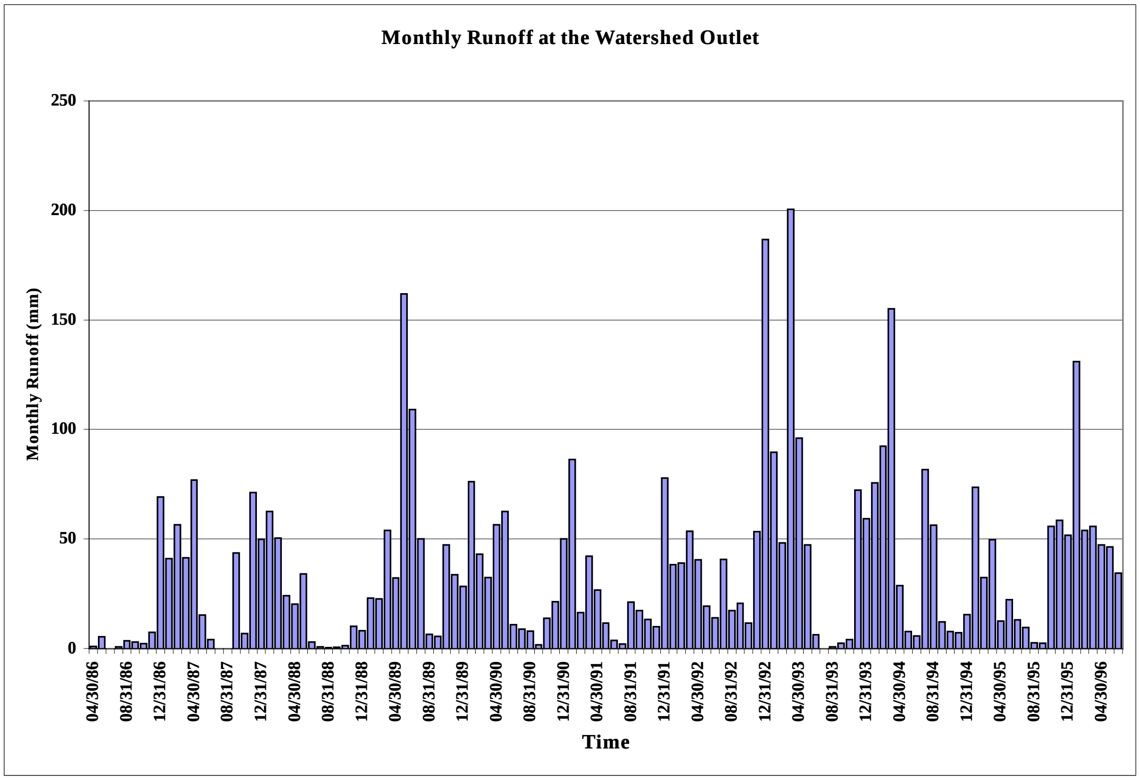

Figure A.1 Monthly runoff total at the watershed outlet

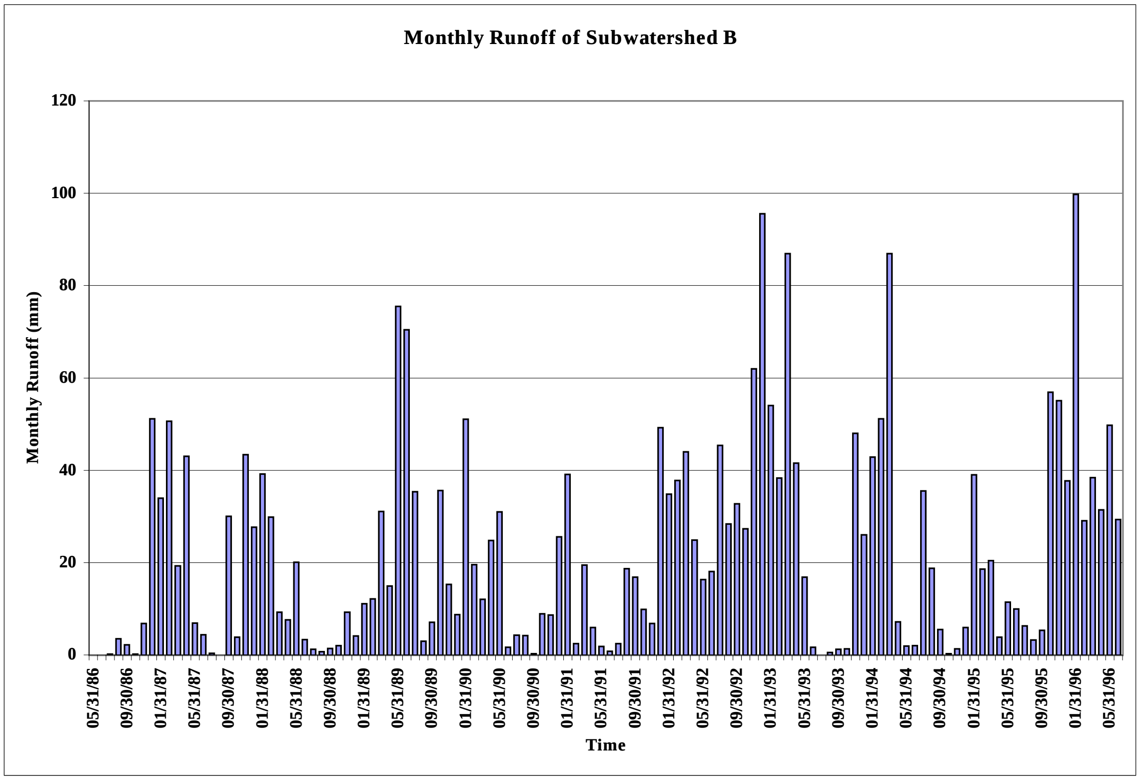

Figure A.2 Monthly runoff totals from subwatershed QOB

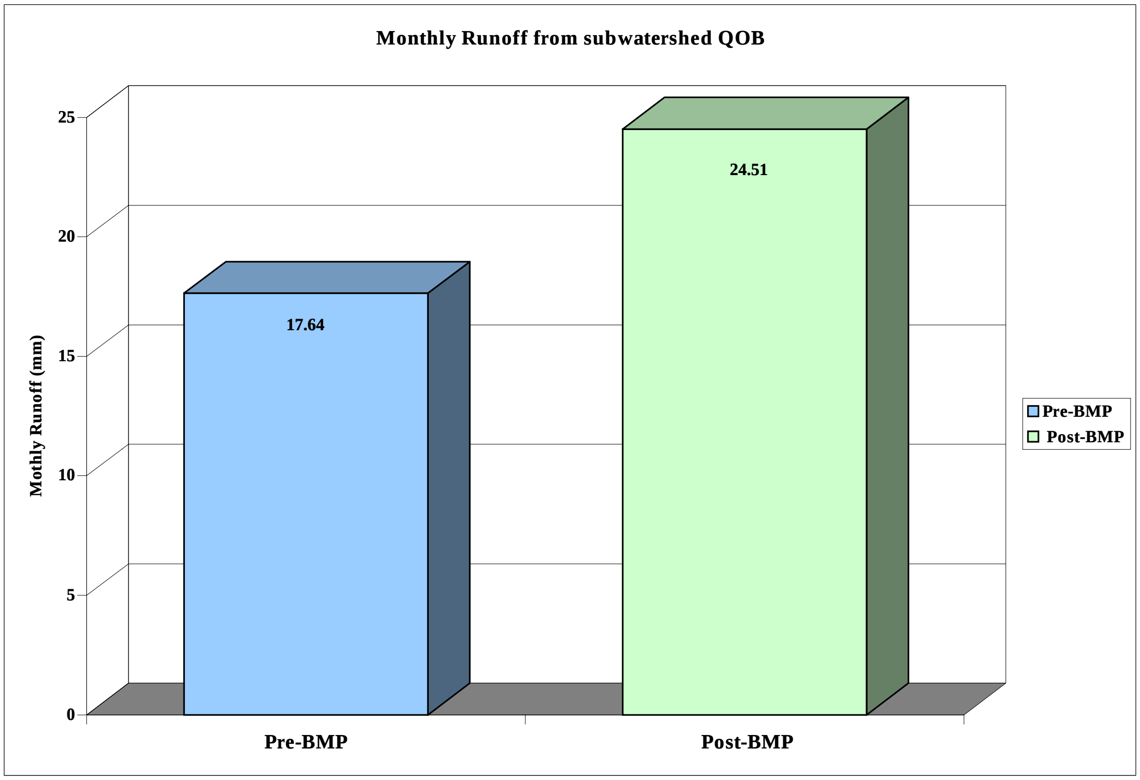

Figure A.3 Comparison of pre- and post-BMP monthly runoff totals from subwatershed QOB

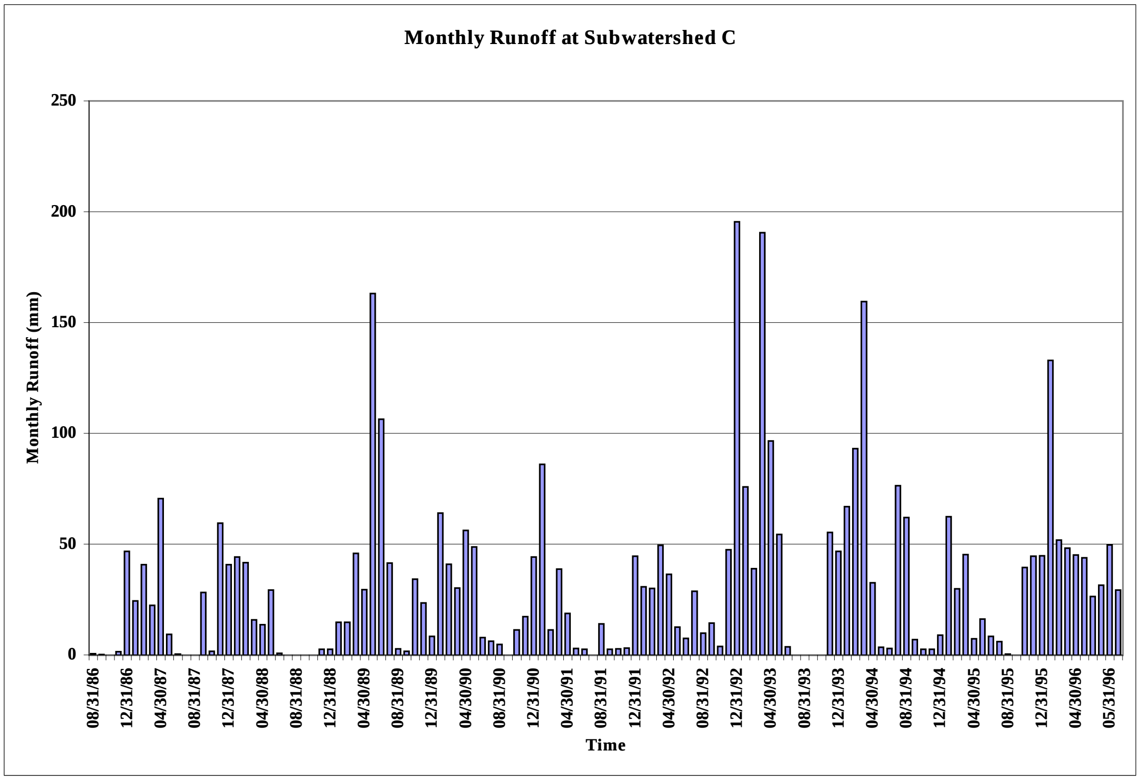

Figure A.4 Monthly runoff totals from subwatershed QOC

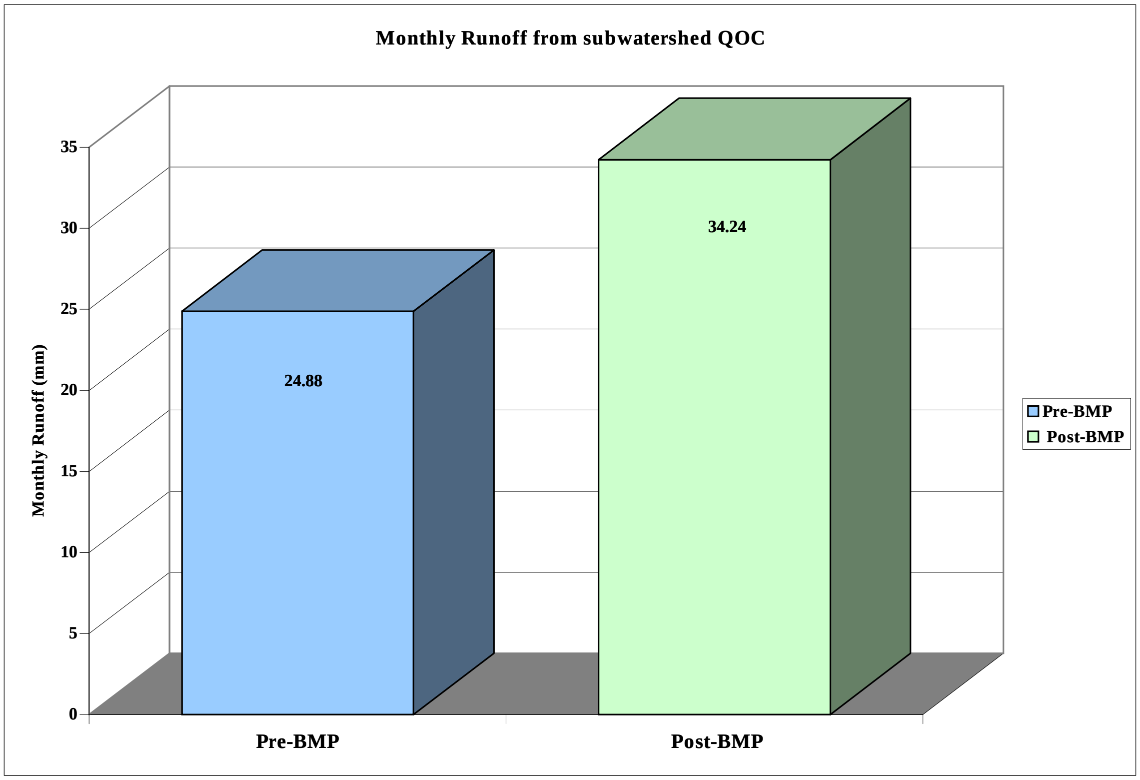

Figure A.5 Comparison of pre- and post-BMP monthly runoff totals from subwatershed QOC

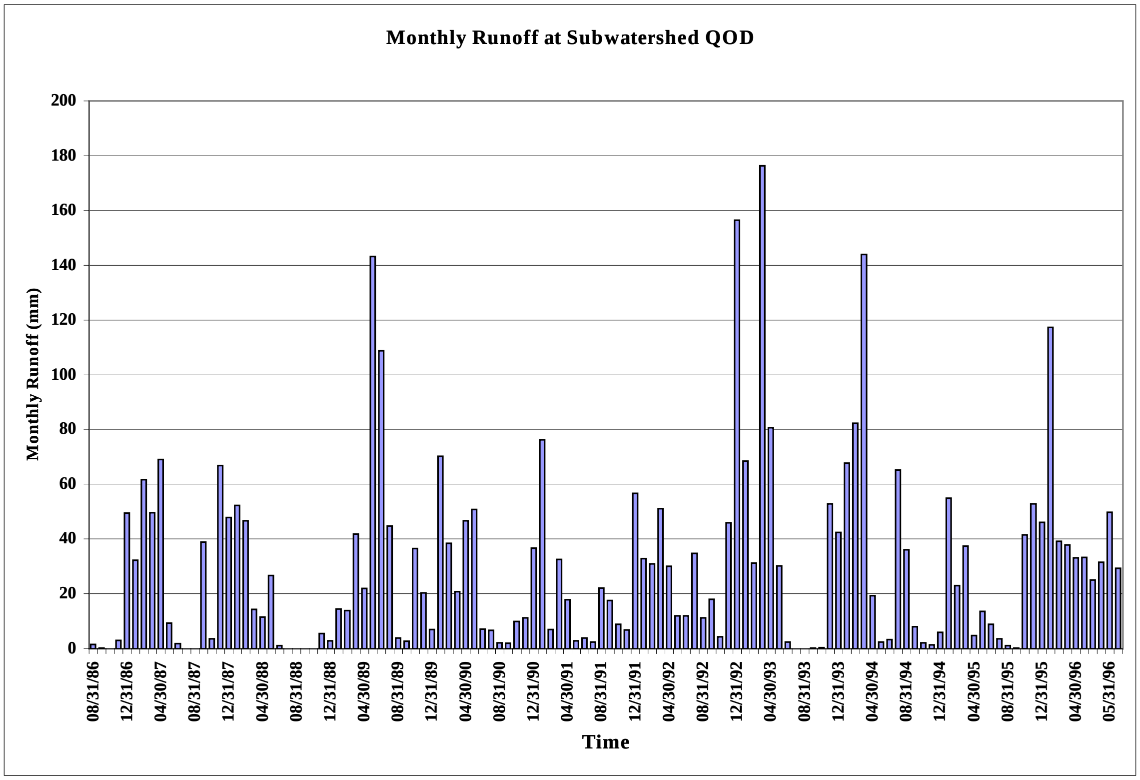

Figure A.6 Monthly runoff totals from subwatershed QOD

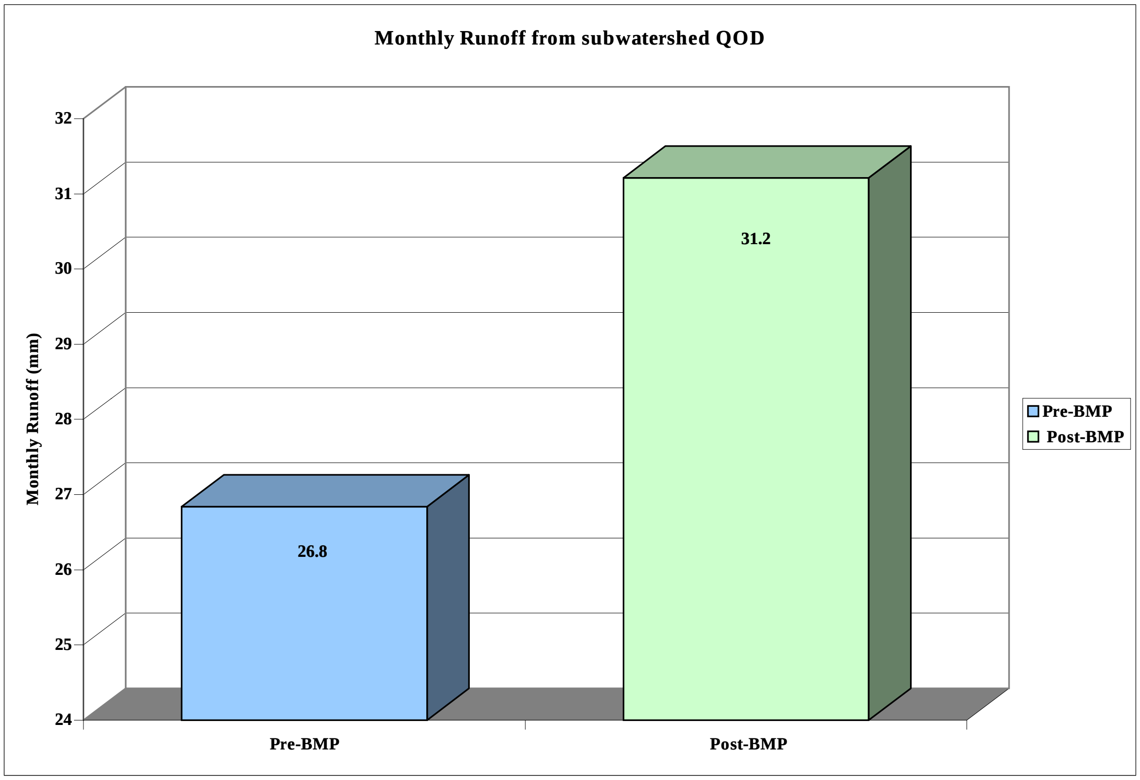

Figure A.7 Comparison of pre- and post-BMP monthly runoff totals from subwatershed QOD

Vita

Mary Nicole Cook completed the degree requirements for a Bachelor of Science in Environmental Science, Aquatic Resources option, at Virginia Tech in May, 1994. During the summer of 1996, she enrolled as a full-time Master's candidate in the Biological Systems Engineering Department, also at Virginia Tech. Upon completion of her Master's degree, she will undoubtedly leave Blacksburg, much to the surprise of most of her family and friends.