Field assessment of bacteria and nutrient removal by vegetative filter strips

Kyle R. Douglas-Mankin

(*Department of Biological and Agricultural Engineering, Kansas State University, USA*)

Abstract: Strategies are sought to reduce the impact of nonpoint sources of pollution, including fecal bacteria, and meet TMDL criteria. Vegetative filter strips (VFSs) are one such strategy, though data of VFS function under field conditions, particularly for fecal bacteria, are limited. The objective of this study was to evaluate the efficiencies in removing fecal bacteria, N, and P from VFSs installed to treat contaminated runoff from a working feedlot. VFSs were found to be effective in removing abroad range of constituents from beef feedlot runoff pretreated by a settling basin. The first 30 m provided most or all of the reductions found within the 150 m VFSs studied: reductions average 85% of inflow water, 85% of sediment, 77% of N, and 84% of P. Fecal bacteria removal by the VFSs was about one order of magnitude: reductions at 30 m ranged from 83.5% for FC and FS to 91% for *E. coli*. On the site being studied, this provided an important level of protection and reduced surface-flow concentrations of fecal coliforms to below the 200 cfu/100 mL (coliform-forming units, cfu) water-quality standard for Kansas.

Keywords: bacteria, vegetative filter strips, livestock waste management, vegetative treatment areas

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1 Introduction

Contamination of surface waters by fecal pathogens, nutrients, and sediments are increasingly important environmental issues. The Clean Water Act (33 U.S.C. §§ 1251−1387) mandates the total maximum daily load (TMDL) program to identify, quantify and remediate water-quality issues, including bacteria[1]. In Kansas, the Unified Watershed Assessment identified and prioritized watersheds that were impaired for restoration. Of the top ten watersheds identified for restoration in Kansas, all were impaired by fecal coliform bacteria; and 91% of lake area had impairment from nutrient enrichment (eutrophication)[2]. The state completed its first round of TMDL designations in 2003. Strategies are sought to reduce the impact of nonpoint sources of pollution and meet these TMDL criteria. Expanding the list of affordable, effective management practices available to address contamination from each category of sources would be a major benefit.

Livestock feedlots are major sources of bacterial and nutrient contamination to surface waters in many watersheds[3]. Livestock operations with 1 000 or more animal units are regulated via the National Pollutant Discharge Elimination System (NPDES). The state of Kansas requires operations with 300 or more confined animal units to be registered with the Kansas Department of Health and Environment (KDHE). However, most smaller livestock operations currently are not regulated. Many of these smaller operations are located along streams, waterways, or road ditches, which may drain directly to surface water sources.

Human ingestion of water contaminated with microbial pathogens may result in intestinal illness or even death[1]. Fecal coliform (FC) concentrations are used to indicate the presence of other disease-causing bacteria. Water quality standards for FC bacteria in Kansas were set by KDHE[4]. Bacterial limits in surface

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Corresponding author's email: krdm@ksu.edu.

water vary depending on its intended use. In drinking water, the maximum contaminant level for FC is 0 coliform-forming units per 100 mL (abbreviated 0 cfu/100 mL). Waters used for primary contact, such as swimming, have a maximum allowable FC limit of 200 cfu/100 mL. Waters used for secondary contact, such as boating and fishing, have a maximum FC limit of 2 000 cfu/100 mL. The criteria were changed from FC to *Escherichia coli*[5], with the most stringent (Class A, primary contact) stream segments limited to a calendar-month geometric mean of 160 cfu/100 mL (April 1 to October 31) and 2 358 cfu/100 mL (November 1 to March 31) and secondary contact (Class A) stream segments limited to calendar-month geometric mean of 2 358 cfu/100 mL all year.

Excessive amounts of nutrients have impacts on the surface-water environment as well as on humans. Nutrients of concern are primarily nitrogen (N) and phosphorus (P). Excess concentrations of N and P in surface water contribute to eutrophication and hypoxia of lakes and estuaries[6]. Eutrophication and the related production of algae can cause taste and odor problems in drinking water. Algal blooms also can deplete the dissolved oxygen concentrations in the water, which may kill resident fish and disrupt other inhabitants of the lake. High N concentrations (in the form of nitrate, NO_3) in water consumed by infants may contribute to infantile methemoglobinemia, or blue baby syndrome. However, new research suggests that nitrate in drinking water may not be the sole cause of this illness and casts doubt on the current US EPA drinking-water standard of 10 mg/L NO_3-N[7].

Water quality has become a concern for Kansas reservoirs. The study site is within the watershed draining to Hillsdale Lake, constructed in the early 1980's as part of a comprehensive flood control plan for the Osage and Missouri River basins. Hillsdale Lake provides water for the city of Olathe and many surrounding communities. Runoff from livestock feedlots is considered an important potential source of pollution for this lake.

Common management practices for controlling pollution from livestock feedlots include lagoons and vegetative filter strips (VFSs)[8-10]. Lagoons collect and store the waste until it can be applied to the land. A VFS is used with a lagoon or settling basin to slow runoff and reduce pollutant levels from a source before the pollutant can reach a surface water body. A VFS is a band of vegetation down slope of cropland or an animal production facility designed for the removal of sediments, organic matter, nutrients, agrochemicals, and bacteria from runoff and wastewater before these pollutants reach receiving waters. The main application of VFSs is the treatment of non-point source pollution generated by agricultural and livestock production activities. The mechanisms of removal vary by pollutant and may include the processes of settling, filtration, dilution, absorption of pollutants, infiltration, volatilization, vegetative consumption, and decomposition[10-13].

VFSs have been proven effective in solids reduction. Studies indicate that solids concentration can be reduced by up to 98% between the inlet and outlet of a filter strip. However, most reductions are in the 70% to 90% range[10,14]. Variation within this range is attributed to the site-specific conditions such as vegetation, soil type, flow conditions, size of the filter strip, and influent solids concentration of the wastewater. It is important to note that most of the solids removal often occurs in the first meter or several meters of the filter strip. This suggests that the primary removal mechanism for solids may be settling caused by decreased runoff velocity. This decrease in velocity may result from backwater effects at the leading edge of the VFS, infiltration into soil, or other vegetation-related effects within the VFS. However, when wastewater is pumped from lagoons or storage structures and distributed to the upstream edge of a VFS, a large portion of settleable solids typically have been removed, and the remaining solids are removed more evenly throughout the VFS.

Assessing N reductions that occur in VFSs is more complex than assessing solids reduction. The most common measures of N content in surface runoff include total N, total Kjeldahl N (TKN), ammonium and ammonia (NH_4 and NH_3, respectively), and nitrate (NO_3). Past research has shown that VFSs can reduce concentrations of total N, TKN, NH_4, and NH_3 by 85% or

more. In contrast, NO_3 removal by filter strips is much lower, and effluent concentration often exceeds that of the influent. This can be misleading, however, and indicates that nitrification is occurring in the VFS. Even filter strips that exhibit increasing NO_3 concentrations typically result in overall N reductions. Ammonia volatization is another process occurring in filter strips that contributes to N reduction and odor-related byproducts. If runoff is shallow, uniform, and has low velocity, a small portion of NH_3 is often lost to the atmosphere. This results in slightly higher reductions of total N, TKN, and NH_3.

Total P removal often reflects the effectiveness of the VFS for solids removal. Phosphorus readily sorbs to soil particles, particularly clays, that are carried by the runoff. Similar to solids removal, reduction percentages for total P are often between 70% and 95%, Ortho-phosphate is generally assumed to be soluble, and therefore removal efficiency is consistently lower than that of total P[10].

Reported FC reductions by VFSs are highly variable in comparison to solids and nutrients[10]. An important observation is that studies with simulated conditions report higher FC reductions than field studies. Mankin et al.[15] found strong sorption of *E. coli* to clay loam soil but not sand when bacterial solution was passed through disturbed soil columns, with up to 99.7% sorption on the clay loam soil. This result clearly demonstrates that contact of bacteria with clay particles during infiltration and percolation can be an important bacterial detention and removal process in VFS soils.

Lim et al.[16] found that all FCs were removed in the first 6.1 m of a VFS used to treat runoff from a simulated pasture. However, no other studies were found that observed FC removals near 100% for any VFS length, and it is unclear what factor(s) contributed to such effective FC removal. The same filter strip did not remove a greater percentage of nutrients or solids than many other filters that were studied. Edwards et al.[17] found no consistent relationships between the presence of cattle on grazed pastures in northwest Arkansas and FC and FS concentrations in runoff. However, FC and FS concentrations were affected by the season in which runoff occurred. Larsen et al.[18] found a 95% reduction in FC concentration in dairy feedlot runoff passing through a 1.37 m long VFS. Using simulated rainfall applied to poultry waste-amended soil at the beginning of 4.5 m and 9.0 m VFSs, Coyne et al.[19] found 75% and 91% removal of FC and 68% and 74% removal of FS, respectively. More research is necessary to obtain reliable estimates of fecal microorganism reduction percentages attainable by VFSs under simulated and operational conditions.

Bingham et al.[20] investigated the effect of VFS length to waste-source length ratio. In this study, the widths of the VFS and waste source were equal, so this can also be viewed as a ratio of areas. Results indicated that concentration reductions occurred with VFS to waste-area ratios of 0.5 and 0.75. However, to approach background levels, an area ratio of 1.0 was necessary. Treatment rates often increase as the VFS to waste-area ratio increases[21-23]. Mankin et al.[14] found average *E. coli* concentration reduction to range from 67.5% to 96.0% on four VFSs in Kansas. They found area ratio was significantly related to *E. coli* population (mass) reduction, with better treatment for VFS with area ratios >0.5. However, their study estimated VFS inflow and outflow volumes, which limited accuracy of their nutrient-mass and bacterial-population reduction analyses.

Although much work has been done using VFSs for cropland runoff, more research is needed to examine VFS effectiveness for treating livestock wastewaters. Researchers have attained fairly consistent removal efficiencies of solids, total N, and total P, particularly under controlled rainfall and plot conditions. However, one of the biggest challenges facing VFSs is attaining effective performance under actual field conditions. Therefore, the objective of this study was to evaluate the efficiencies in removing fecal bacteria, N, and P from VFSs installed to treat contaminated runoff from a working feedlot.

2 Methods

2.1 Site description

The project site is located on a farm 8 km (5 mi) south

of Gardner City, Kansas in the Lower Marais des Cygnes Watershed. The feedlot has a capacity of 300 head of starter heifers. Runoff from the cattle feedlot goes first to a settling basin; then, six 13 cm (5-in.) (ID) exit pipes distribute the runoff to three parallel VFSs (two exit pipes for each VFS). Two of the three VFSs were studied (Figure 1). The VFSs, having 2% average slope and 14 to 15 m average width each, were planted to fescue (1994) in Newtonia silt loam soil. Runoff samples were obtained at three locations along the length of each VFS: one sample at an inlet pipe, a second sample 30 m from the inlet, and a third sample 150 m from the inlet. Steel sheets 0.6 m high were driven 0.1 m into the ground to direct runoff to the cutthroat flumes located in the center of the VFS. The steel sheets followed a 0.5% slope on the ground. The exit flow from each flume was redistributed back to the VFS by two 41 cm (16-in.) bottom-perforated flexible polyethylene tubes. The tubes were anchored following a 0.5% slope away from each flume to each side of the VFS.

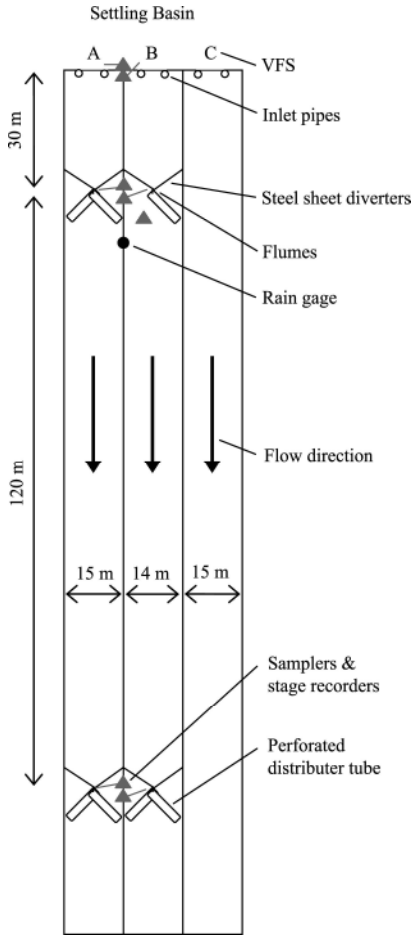

Figure 1 Site diagram for study VFSs

2.2 Sampling and analysis

Samples were collected using portable samplers (ISCO Inc., Lincoln, NE, Model 6700) equipped with stage recording bubbler modules (ISCO Inc., Lincoln, NE, Model 730) to measure water levels and enable sampling. The samplers installed at the inlet pipes used the bubbler modules to detect the height of the water in the settling basin. For the samplers installed at 30 m and 150 m points in the VFS, the bubbler modules were used to detect the water heights in the flumes. For each runoff event from October 2000 to May 2002, 600 mL samples were collected every hour for the first three hours followed by intervals of three or four hours until the end of the runoff event. Upon collection from the field, 200 mL sub-samples were prepared for laboratory nutrient and bacterial content analyses.

The hydrographs for each runoff event were calculated at each sampling location. To calculate the flow from the inlet pipes, Manning's equation was used while the pipe was partially full, and the energy equation (Bernoulli's equation with head loss) was used after the pipe became full. The roughness coefficient of 0.012 was used for PVC in the Manning's equation, and a relative roughness of 0.001 was used to calculate the head loss in the energy equation, using the tabular value for galvanized iron. Using these coefficients, the energy and Manning's equations were found to have continuity at the transition from partially full to full flow, and agreed with the expected total flow based on measured rainfall volumes. The cutthroat flumes were calibrated in the lab to have $Q=0.96H^{1.72}$, where Q is the flow rate (cfs) and H is the height of the runoff in the flume (ft), in agreement with published coefficients for flumes of this configuration[24].

Samples were analyzed for total N and total P using a potassium persulfate digestion[25]. Sediment concentration in the runoff was determined by filtering 100 mL of water with vacuum assist through pre-weighed 0.45-μm pore-size filter paper. After filtering, a sub-sample of sediment was tested for bacteria, as discussed below, and the remaining soil along with the filter papers were dried in an oven at approximately 105℃ for 24 hours and then reweighed to determine sediment mass[26]. The

membrane-filtration method was used for bacterial enumeration[26]. Three volumes (0.1 mL, 1 mL, and 10 mL, or as appropriate for expected concentrations) of the original water sample were filtered using 0.45 μm gridded sterile filter paper and then placed into different media: media mFC (Difco Brand, BD, Franklin Lakes, NJ) for fecal coliforms and KF (Difco Brand, BD, Franklin Lakes, NJ) for fecal streptococci. The mFC plates were incubated at 44.5℃ for 24 h and KF plates incubated at 37℃ for 48 h. After the mFC plates were counted, the filters were transferred to MUG (4-methylumbelliferyl-b-D glucuronide, Difco Brand, BD, Franklin Lakes, NJ) media and incubated for four to six hours at 37℃ for *E. coli* enumeration. The microbial counts of each sample within the ranges of 30 to 300 cfu for fecal streptococci or 20 to 200 cfu for fecal coliforms and *E. coli* were recorded.

Using the concentration of each sample in a runoff event, rectangular integration was used to calculate the total mass transported through each sampling point. The concentration at a sampling time was assumed to hold from the mid-point of the previous sampling interval to the mid-point of the next sampling interval. The same principle was used to calculate the populations of bacteria transported. The bacterial numbers were given in cfu/mL.

3 Results and discussion

Although power outage and equipment malfunctions prevented complete data from being collected at each sampler location for many events, adequate data were collected to determine mass reductions for a total of 10 VFS-events over a 13 month period (Table 1). After 30 m of VFS length, a net of 85.0% of inflow water had been removed, presumably by infiltration, and 85.0% of sediment had been removed, most likely due to sedimentation or mass advection into soil with infiltrated water. Average mass reductions for N (77.0%) and P (84.0%) were measured. These data are similar to many other reported studies on VFSs, as discussed above.

Table 1 Mass reduction of constituents between the inlet and the position indicated (30 or 150 m) by event for two parallel VFSs (*A* and *B*)

Month	Event	VFS	Position	V_{total}	TSS	TDS	*N*	*P*	*K*	FC	*E. coli*	FS
May 2001	1	*A*	30 m	99.8%	93.2%	58.4%	75.8%	83.5%	N/A	81.0%	92.2%	77.1%
May 2001	1	*B*	30 m	100.0%	99.6%	99.5%	99.5%	99.6%	N/A	95.9%	99.6%	99.8%
June 2001	2	*A*	30 m	83.2%	93.2%	78.1%	86.9%	82.7%	N/A	-298126%*	-12120855%*	-157482%*
Sept 2001	3	*A*	30 m	82.3%	92.5%	73.8%	61.3%	86.9%	79.2%	72.8%	79.1%	69.2%
May 2002	6	*A*	30 m	59.0%	85.4%	58.9%	61.7%	67.0%	58.7%	84.2%	92.1%	87.8%
Average				84.9%	92.8%	73.7%	77.0%	83.9%	69.0%	83.5%	90.8%	83.5%
May 2001	1	*A*	150 m	66.9%	97.0%	61.6%	71.0%	81.9%	N/A	92.4%	97.7%	94.1%
Sept 2001	3	*A*	150 m	99.8%	99.9%	99.6%	99.5%	99.9%	99.8%	100.0%	100.0%	99.8%
April 2002	4	*A*	150 m	99.8%	95.4%	49.1%	84.4%	61.3%	51.5%	74.9%	71.3%	72.1%
April 2002	5	*B*	150 m	78.1%	93.5%	N/A	79.9%	83.3%	78.7%	93.4%	96.1%	87.8%
May 2002	6	*A*	150 m	63.6%	90.8%	61.9%	70.6%	68.3%	53.4%	64.8%	82.0%	83.6%
Average				81.6%	95.3%	68.1%	81.1%	78.9%	70.9%	85.1%	89.4%	87.5%

Note: V_{total} = total flow volume, TSS = total suspended solids, TDS = total dissolved solids, *N* = total inorganic nitrogen, *P* = total phosphorus, *K* = total potassium, FC = fecal coliform bacteria, *E. coli* = *Escherichia coli*, FS = fecal streptococci bacteria.

*Outliers omitted from calculated averages.

Compared to the first 30 m, the next 120 m of VFS provided little or no additional reductions from inflow concentrations (Table 1). This confirms the importance of the first segment of VFS for removal of sediments and other attached constituents. This study did not aim to resolve the reasons for this trend, but its consistency across a broad range of constituents suggests that increasing VFS length does not necessarily translate into corresponding increases in effectiveness. These data appear to suggest a limit to the reductions possible from a VFS and perhaps the existence of a "background" level that cannot be surpassed.

Bacteria population (mass) removals at 30 m ranged from 83.5% for FC and FS to 91.0% for *E. coli*. These

removals translate into $\log_{10}$ reductions of 0.8 to 1.0. Although reductions of one order of magnitude (about 1 $\log_{10}$) provide some protection of water resources, these reductions may still allow a large number of bacteria to exit the VFS. For the study system, however, the VFSs added a level of protection that would allow outflow to meet current limits for fecal bacteria in streams. For example, total inflow populations of fecal coliform bacteria during the study period averaged 9.3×10^9 cfu per event, or 750 cfu/100 mL of average inflow (Table 2). This exceeds the state primary contact limit of 200 cfu/100 mL. Accounting for the average reductions from the VFS reduces the average outflow (at 150 m) by 85.1% (Table 1) to 112 cfu/100 mL (or <200 cfu/100 mL).

Table 2 Average volume (V_{total}), mass (TSS, TDS, N, P, K), or population (FC, *E. coli*, FS) inflow to each VFS during study period (n = 11, May 2001 to May 2002)

V_{total} /m^3	TSS /kg	TDS /kg	N /kg	P /kg	K /kg	FC /cfu	E. coli /cfu	FS /cfu
1243	114	121	6.9	1.1	12	9.3E+09	2.9E+09	2.7E+09

4 Conclusions

This study was one of very few published studies to measure mass reductions of sediment, nutrients and fecal bacteria from VFSs located on a working beef feedlot facility. VFSs were found to be effective in removing abroad range of constituents from beef feedlot runoff pretreated by a settling basin. The first 30 m provided most or all of the reductions found within the 150 m VFSs studied. Fecal bacteria removal by the VFSs was on the order of 1 log; on the site being studied, this provided an important level of protection and reduced surface-flow concentrations of fecal coliforms to below the 200 cfu/100 mL water-quality standard for Kansas.

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