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ESTABLISHMENT OF A DAIRY WASTEWATER TREATMENT SYSTEM: INTEGRATING A LAGOON, WETLANDS AND VEGETATIVE FILTER STRIPS

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Summary: An Ecological Livestock Pollution Control system, comprised of a settling basin, a lagoon or holding pond, wetlands, and vegetative filter strips in series, was designed to treat the wastewater produced on a 200-head dairy operation. This paper will provide a summary of (1) design of the lagoon, wetlands, and vegetative filter strips; (2) system establishment, including the planting design; (3) instrumentation and preliminary data collection; and (4) expected treatment based on current literature.

Keywords: Water quality, Waste Management Systems, Dairy waste management.

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Abstract

An Ecological Livestock Pollution Control system, comprised of a settling basin, a lagoon or holding pond, wetlands, and vegetative filter strips in series, was designed to treat the wastewater produced on a 200-head dairy operation. This paper will provide a summary of (1) design of the lagoon, wetlands, and vegetative filter strips; (2) system establishment, including the planting design; (3) instrumentation and preliminary data collection; and (4) expected treatment based on current literature.

Introduction

Currently there are more than 600 dairies in Kansas. Many of these dairies are located in watersheds that are being targeted for watershed restoration (Snethen and Prophet, 1998) and are or may become targets for Total Maximum Daily Load (TMDL) development because of stream sampling data that indicates seasonally high levels of fecal coliform bacteria, nutrients, and/or sediment.

Each year, a 50-cow dairy produces about 909 Mg (1000 tons) of manure, 4770 kg (10,500 lb) nitrogen (N), 2640 kg (5800 lb) phosphorus (P), and 3770 kg (8300 lb) potassium (K). A portion of these nutrients can leave a dairy as runoff during rainfall events if left uncontrolled. Sediment may also runoff and enter surface water flow from uncontrolled earthen loafing areas.

Constructed wetlands may provide an alternative or supplement to lagoons in wastewater management. In addition, vegetative filter strips (VFSs) can provide localized erosion protection and contaminant reduction in surface runoff waters. Although wetlands have been studied for treating a variety of wastes and VFSs have been used and studied extensively for treating cropland runoff, more research is needed to examine their effectiveness for treating livestock wastewaters, particularly on full-scale, working systems. Each of these systems may be critical in meeting water quality targets, particularly with environmental regulations such as TMDLs becoming more strictly enforced. Therefore, factors affecting treatment effectiveness of full-scale treatment wetlands and VFSs must be better quantified, to develop design standards.

The Carl Nichols Dairy currently houses a 200 cow mixed dairy herd. The Ecological Livestock Pollution Control system outlined in this paper is representative of a type of system that may have broad applicability across Kansas for dairy wastewater management, although it was designed specifically for the hydrology and site conditions at the Nichols Dairy.

This paper will discuss the establishment of this system:

1. Design of the lagoon, wetlands, and vegetative filter strips,
2. System establishment,
3. Instrumentation and preliminary data collection,
4. Expected treatment, and
5. Preliminary data.

This overall goal of this project will be to provide the data needed to: 1) quantify the level of treatment offered by the current system in response to various waste loading rates, environmental and hydrologic conditions, and management practices; 2) describe system responses over time, including nutrient accumulation in soils and sediments, vegetative establishment and diversity, and wildlife/ecosystem dynamics; and 3) support development of a baseline model of the wetland and vegetative filter system that will help refine the design of future systems to meet the demands of different environmental and hydrologic regions in Kansas.

System Design

The Ecological Livestock Pollution Control system at Carl Nichols Dairy, Anderson County, Kansas, was designed using both wetlands and vegetative filter strips to treat dairy wastes (Figure 1). Wastewater from the milking parlor directly enters a settling basin before flowing into a 130-m (430-ft) length, 0.12-ha (0.3-acre), horseshoe-shaped wetland. Outflow from the horseshoe wetland along with runoff from 1.0 ha (2.5 acres) of concrete and dirt lots flows into a sediment basin and then a lagoon, designed to retain runoff from a 25-year, 24-hour storm. Water is then discharged to two 0.20-ha (0.5-acre) wetland cells in series. Water from the second cell exits to two 150-m (500-ft) length, 0.32-ha (0.8-acre) vegetative cells, and then flows across a 0.32-ha (0.8-acre) filter area that may be planted to trees.

Settling Basin. A trapezoidal settling basin collects runoff from 0.325 ha (35,000 ft^2) of earthen lot and 0.650 ha (70,000 ft^2) of concrete drainage lot. It was sized to retain runoff from a 10-yr, 24-hr storm in addition to a sedimentation allowance. The total capacity of the sedimentation basin was 0.303 ha (32,600 ft^3) at 1.22 m (4.0 ft) total depth, not including 0.75 ft (10,754 ft^3) freeboard. Water is released through a 6 in PVC pipe set 0.23 m (0.75 ft) above the bottom of the basin and fitted with a vertical riser having four 2100-mm^2 holes/m (2-in^2 holes/ft), minimum.

Lagoon (Holding Pond). The lagoon was sized to meet KDHE requirements for containment structures based on the 25-yr, 24-hr storm (16.5 mm, 6.5 in) and rainfall retention. Water can be released from the lagoon to wetland 1 through a 76-mm (3-in) PVC pipe at a maximum rate of 13.0 L/s (27.5 ft^3/min). A gate valve allows water flow out of the lagoon to be controlled. Seepage was estimated to be approximately 1.5 mm/day (0.06 in/day). Holding pond capacity was 3817 m^3 (134,779 ft^3), plus 1526 m^3 (53,890 ft^3) with 0.6 m (2.0 ft) freeboard.

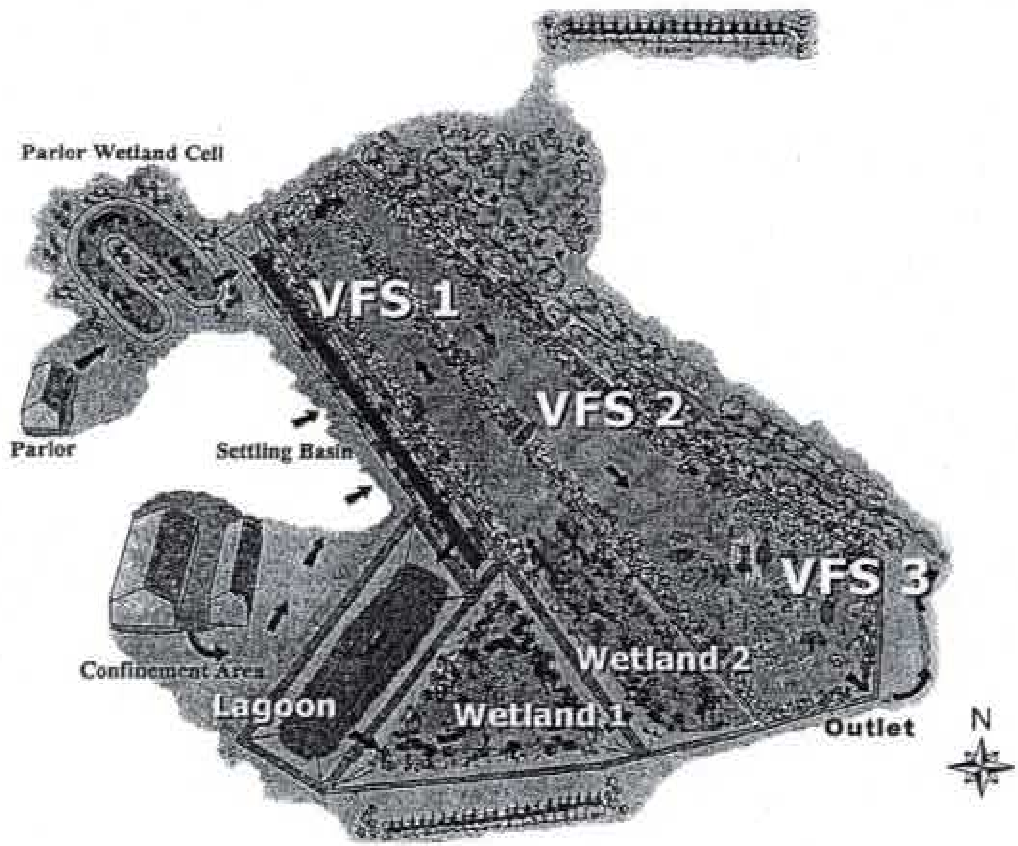

Figure 1. Ecological Livestock Pollution Control System at Nichols Dairy.

Wetlands. Wetland 1 is triangular-shaped with a surface area of 0.3 ha (25,600 ft^2) and was designed to be maintained at 0.45 m (1.5 ft). Two diversions have been added to create a serpentine flow along a path 18.3 m (60 ft) wide and 145 m (475 ft) long (length-to-width ratio of 8:1). Wetland 2 has a surface area of 0.21 ha (22,700 ft^2) with length-to-width ratio of 2.5:1 and was designed to be maintained at 0.15 m (0.5 ft). Inflow to wetlands 1 and 2 each are controlled by 76-mm (3-in) pipes with gate valves. At the maximum flow rate of 13.0 L/s (27.5 ft^3/min), these wetlands have detention times of about 1.0 and 0.3 days, respectively. The outflow from wetland 2 is a span of ten 150-mm (6-in), 90° V-notch weirs. The milk parlor (horseshoe) wetland has surface area of 0.119 ha (12,800 ft^2), which corresponds to a 32-day detention time at a constant flow rate of 0.13 L/s (400 ft^3/day).

Vegetative Filter Strips. Water discharging Wetland 2 overflows across two 150 m (500 ft) by 23 m (75 ft) (average width) vegetative cells planted to Eastern-gamma grass and then across a 0.32-ha (0.8-acre) filter planted to trees. The final system outlet is through a 200-mm (8-in) PVC pipe which discharges to a waterway that drains directly to a stream.

System Establishment

The site is located in northwest Anderson County, Kansas, 0.8 km (0.5 mi) west of Pottawatomie Creek, at the intersection of two waterways draining into the Creek. The soil on this site is Kenoma, which has a silt loam in the upper 0.18 m (7 in), silty clay from 0.18 to 1.42 m (7 to 56 in), and silty clay loam from 1.42 to 1.55 m (57 to 61 in). The water table as determined by the well on the property is approximately 30 m (100 ft) below the surface.

Construction was completed in March 1999. More than 2500 trees, shrubs, and wetland plants were planted in and along the system. The planting design was planned to meet water treatment and landowner objectives, such as wildlife habitat and alternative hardwood income. Wetland plants, including cattail, bulrush, horsetail, and reed canary grass, were dug by hand and transplanted in April and May 1999. Vegetative filter strips were planted to Eastern-gamma grass in May 2000. Due to drainage problems, no hardwoods were planted as planned (walnut, silver maple, green ash) in the final portion of the VFS, though this phase may be implemented if water conditions can be corrected. Along the banks of all cells, a number of deciduous shrub species were planted: chokecherry, American plum, golden current, fragrant sumac, silky dogwood, redosier dogwood, hazelnut. In addition, the margins of the wetland cells also were planted with streamco willow, dwarf bankers willow, buttonbush, and elderberry. The filter strip will appear to be a woody draw to the casual passerby. No trees or shrubs were planted near the lagoon.

System Instrumentation

Automated samplers (ISCO 6700, Isco Inc., Lincoln, NE) have been installed in protective box enclosures at the outflows to the lagoon, wetland 1, wetland 2, and the final VFS. Water stage is measured at each sampler using a bubbler module (ISCO 730, Isco Inc., Lincoln, NE) that measures liquid level above the outlet of a bubble line using a pressure transducer. Flows into wetland 1 and 2 are calculated using pipe-flow equations with known head and pipe dimensions. A permanent weir (ten 90° V-notches at constant elevation on 2.4-m (8-ft) spacing) at the outflow to wetland 2 has been designed and installed. The bottom of the V-notches set the wetland 2 water level at 0.15 m (0.5 ft). Outflow from wetland 2 is calculated using weir-flow equations with known head. Final VFS/system outflow is calculated using a cutthroat flume with known head and flume dimensions (Skogerboe et al., 1972).

The horseshoe wetland for treatment of milk-parlor wastewater is not complete, so no monitoring equipment has been installed there. Plans are for inlet and outlet monitoring using Isco 6700 samplers, Isco 730 bubbler modules, and pipe-flow calculations. A weather station has been configured and installed on-site.

All wetland inlet/outlet and runoff water samples will be analyzed for a suite of water quality parameters: 5-day biochemical oxygen demand (BOD_5) or chemical oxygen demand (COD); fecal coliform bacteria (FC), *Escherichia coliform* bacteria (*E. coli*) and/or *Cryptosporidium parvum* oocysts (*C. parvum*); total suspended solid (TSS); total nitrogen (TN), ammonium nitrogen (NH_4-N), and nitrate nitrogen (NO_3-N); and total phosphate phosphorus (TP), and orthophosphate phosphorus (ortho-P). Soil samples from the wetland and VFS soils will be analyzed for texture, organic matter, TN, NO_3-N, TP and Bray P.

Expected Treatment

Wetland Overall Performance

Physical, biological and chemical reactions are responsible for pollutant reduction in wetland systems. Filtration and sedimentation remove particulate organic and inorganic components of wastewater. Microbes act upon the wastewater constituents with metabolic process reducing nitrogen content and organic matter in the wastewater. Chemical transformations are largely responsible for phosphorus, virus, and bacteria removal (Reaves et al., 1994). The overall reduction rate of pollutants varies with loading rates, time of the year, vegetative types and the age of the wetland system.

CH2M Hill and Payne Engineering (1997) summarized an average overall removal rate for BOD_5, TN, TP, TSS, and NH_4-N from their Livestock Wastewater Treatment Wetland Database (Table 1). In a detailed synthesis of the recent wetland literature (Wang and Mankin, 2000), similar averages are presented. However, significant variability within and among systems is clearly evident. Reported treatment rates varied from 60 to 99% for BOD_5, 43 to 97% for N, and 28 to 99% for P.

Table 1. Average Removal of BOD_5, TSS, NH_4-N, TN and TP (CH2M Hill and Payne Engineering, 1997).

Parameters	Average Inflow concentration (mg/L)	Average Outflow concentration (mg/L)	Average Concentration Reduction (%)
BOD_5	404	129	68
NH_4-N	74.3	30	59.6
TSS	914	432	53
TN	129.2	47.7	63
TP	24.3	14.1	42

Schaafsma et al. (2000) studied a system with a settling basin, wetland cells and VFS, a configuration similar to that found at Nichols Dairy. The overall system significantly reduced the levels of most wastewater constituents in dairy barnyard wastewater. Nitrate/nitrite levels increased significantly across the system, consistent with the general increase in dissolved oxygen levels. Tanner et al. (1995) found BOD was reduced by 80%, suspended solids 75-80%, total nitrogen 75%, and total phosphorus 74%. A system monitored by Karpiscak et al. (1999) had an overall BOD_5, TSS, total Kjeldahl N, organic N, NH_4-N and FC reduction of 91%, 83%, 63%, 69%, 59% and 99.94%, respectively. These studies are indicative of the wide range of treatment effectiveness observed for constructed wetlands receiving dairy waste.

Possible reasons for treatment variability have also been reported. Niswander (1997) indicated that the BOD removal may be related to the BOD loading rate. He reported reductions in BOD of 52% with an average loading of 188 kg/ha/d. By comparison, Geary and Moore (1999) reported greater average reductions (61%) with smaller average loading (56 kg/ha/d). [Note: Nichols Dairy estimated average loading rate is less than 10 kg/ha/d.) Nitrogen removal efficiencies also were quite variable. Xue et al. (1999), Geary and Moore (1999), Maschinski et al. (1999) and others suggest that N removal required a complex biofilm of nitrifying and denitrifying bacteria for best performance. Biofilm establishment may take two to three growing seasons.

In general, the long-term removal rate of P in wetlands is much lower than that of solids or BOD. While P may be immobilized in constructed wetlands by plant uptake, adsorption, precipitation, algal uptake and incorporation into biological films, P removal is highly sensitive to loading rate. For example, Geary and Moore (1999) found 28% P removal at a loading rate of 15 kg/ha/d whereas Niswander (1997) reported higher P removal (42%) at a lower loading rate of (12 kg/ha/d). In addition, total removal capacity is considered to be finite, subject to the absorptive ability of the substrate. Geary and Moore (1999) reported that P removal rates were quite low, decreased over time, and occasionally negative (i.e., the wetland released P).

Factors that affect overall wetland performance include vegetative type, season, water depth, hydraulic retention time and the loading rate, and the wetland age (Wang and Mankin, 2000). Since evapotranspiration will have impact on the water balance of the wetland, it should be considered if evaluating system performance based on the concentration removal rate.

All studies have shown a reduction of pollutants in dairy wastewater, though considerable variability existed within and among systems. The constructed wetland systems demonstrate a potential for dairy wastewater treatment, but more data must be collected in order to develop a suitable model that can predict the performance of wetland system more accurately.

VFS Overall Performance

Vegetative Filter Strips are usually evaluated by their ability to reduce pollutant levels in runoff that enters and leaves the filter. The percent reduction of a particular contaminant on a mass or concentration basis is the standard indicator of VFS treatment effectiveness. Most studies are concerned with several of the following pollutants: solids or sediment, N in its various forms, soluble and attached P, some indicator of oxygen demand, and the bacterial quality of the runoff. Specific sites may have concerns with additional pollutants such as pesticides or solvents, but the above list includes the primary concerns of livestock waste. Other VFS performance characteristics of interest include the change in VFS removal efficiency over time and additional treatment gained with increasing filter length. Several researchers have examined these relationships, as they both have strong implications for VFS design.

The major constituents in feedlot runoff requiring treatment are solids, N, P, and fecal bacteria. For each contaminant, overall trends as well as selected cases from the literature will be discussed. A detailed synthesis of the recent VFS literature is presented elsewhere (Ikenberry and Mankin, 2000).

Solids. A relatively large quantity of research exists for solids reduction achieved by VFSs. 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 70-90% range (Ikenberry and Mankin, 2000). 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 few feet of the filter strip.

Nitrogen. Assessing N reductions that occur in filter strips is more complex than solids. Past research has shown that VFSs have the ability to reduce concentrations of total N, total Kjeldahl N, NH_4-N, and NH_3-N by 85% or more (Ikenberry and Mankin, 2000). In contrast, NO_3-N removal by filter strips is much lower, and effluent often exceeds the influent concentration due to nitrification. Even filter strips that exhibit increasing nitrate concentrations typically result in overall N reductions. Ammonia volatization may also contribute to N reduction. If runoff is shallow, uniform, and has low velocity, ammonia is often lost to the atmosphere.

Phosphorus. Total P removal often reflects the effectiveness of the VFS for solids removal, because a large portion of P adsorbs to soil particles that are carried by the runoff. Similar to solids removal, reduction percentages for total P are often between 70 and 95%, although the dissolved ortho-P removal efficiency is consistently lower than that of total P (Ikenberry and Mankin, 2000).

Fecal Coliforms. Reported FC reductions by VFSs are highly varied in comparison to solids and nutrients (Ikenberry and Mankin, 2000). Studies with simulated rainfall tended to report higher FC reductions than systems exposed to natural conditions. Lim (1997) found that all FCs were removed in the first 6.1m of a VFS used to treat runoff from a simulated pasture. No other studies were found that observed FC removals near 100% for any VFS length. 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. More research is necessary to obtain reliable estimates of FC reduction percentages attainable by VFSs.

VFSs can be effective at reducing pollutant transport in runoff and wastewaters generated by livestock operations. While concentration and mass reduction rates are often quite high, effluent concentrations from VFSs are still high, and seldom meet water quality targets when used as stand-alone treatment measures. However, VFSs can be excellent tools in lowering the pollution potential of feedlots, waste storage facilities, and confined feeding operations when used in conjunction with detention ponds, settling basins, lagoons, and/or constructed wetlands. The majority of past VFS research reveals fairly consistent removal efficiencies of solids, total N, and total P. However, FC and nitrate removal seem to be highly variable.

Conclusions

The Nichols Dairy Ecological Livestock Pollution Control System represents a hybrid system of settling basins, lagoon, wetlands, and vegetative filter strips that should prove to be a useful tool for evaluating performance of full-scale dairy wastewater treatment systems in Kansas. Future research will analyze data collected over a minimum of a 2-year period. Together with the experience base generated from other regional, national, and international dairy and livestock wastewater treatment systems, a useful set of criteria for design, construction, operation, and maintenance can be developed for Kansas conditions.

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