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Management Options for Runoff Wastewater from Confined Livestock Winter Feeding Sites

A Review of Treatment Technologies

Canada

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Introduction

Continued and growing water quality problems in nationally significant water bodies (e.g. Lake Winnipeg, Lake Erie) provides the impetus to be proactive in managing agricultural wastewater. Both confined and in-field livestock winter feeding sites have the potential to contribute significant nutrient and pathogen loads to surface water systems. In parts of the prairies, there has been a growing trend to in-field winter feeding systems; however, confined winter feeding sites continue to be used for feeding and or for calving by many producers, and thus the need to address potential pollution from these sites will continue to exist. In other parts of Canada, confined sites constitute the majority of winter feeding sites.

The definition of a confined winter feeding site varies across the country but in general it includes any site where livestock are fed, watered and sheltered for a portion of the winter, and the density of the animals is such that the accumulation of manure must be managed in some way. Confined winter feeding sites differ from extensive in-field winter feeding sites in that the manure accumulation is significantly more concentrated in the confined winter feeding sites. Confined winter feeding sites also differ from intensive feedlot operations in that the cattle are not confined year-round. Each province has specific criteria on what constitutes a confined winter feeding site and whether or not it falls under regulations, but in all cases because of the manure accumulation, the runoff generated during spring melt from these sites is at very high risk of being contaminated. These sites can contribute to both diffuse and point source pollution of surface water bodies.

Currently the management of confined livestock winter feeding sites varies across the country and despite some efforts at developing best management practices (BMPs) there remain gaps in knowledge of treatment options, wastewater characteristics, and the suitability of recommended management practices that have been tested in other regions. For example, although minimum distance setbacks from surface water exist in many jurisdictions, spring runoff often occurs over frozen soils and despite a setback or a diversion, runoff water can still easily reach a water body without much change in its quality. In other cases, although the use of zero-discharge vegetated filter strips (VFS) are a recommended practice in some regions many producers have difficulty in ensuring zero discharge from the filter strip, particularly during the spring freshet.

Objective

This report focuses on the management of wastewater from confined livestock winter feeding sites in cold climates. The objective of this report was to review and synthesize existing information on wastewater management technologies suitable for treating runoff from livestock winter feeding sites to provide better guidance on the appropriateness and the readiness of these technologies to be adopted in specific regions of Canada.

Review Process

A literature review was conducted of published and unpublished studies for the treatment of wastewater from livestock wintering sites, feedlots, and barnyards in Canada and/or regions similar to Canada. The literature review was expanded to include intensive livestock operations and dairy wastewater. Search criteria were established (Appendix I), relevant library databases (e.g. SCOPUS, Google Scholar, ENVIROnetBASE, CAB Abstracts) were queried and the resulting papers were reviewed for applicability to the project. Occasionally additional references were identified from the initial papers reviewed. In addition to the published literature review, provincial agricultural extension specialists were asked to identify and gather information from demonstration projects, trials or other existing works (e.g. unpublished data, unpublished reports, case study information etc.) that may have been completed in each province. A template was created to extract relevant information from each reviewed study ensuring consistency in information collection (Appendix II).

For those technologies where considerable work has taken place, the analyses expanded on former review papers and focused on field-scale studies (see Vegetated Treatment Systems and Constructed Wetlands). For those technologies where limited information was available, some lab-scale studies were included in the review. For all studies, information was extracted on treatment efficacy where possible and summarized as concentration reductions for specific water quality parameters. Specific water quality parameters were selected based on those constituents common in livestock wastewater, as well as those constituents that the majority of studies focused on. These parameters included total suspended solids (TSS), total phosphorus (TP), total Kjeldahl nitrogen (TKN), ammonia (NH_3-N), and biological oxygen demand (BOD).

The technologies are described in six different sections: holding ponds, holding pond *in situ* treatments, vegetative treatment areas, constructed wetlands, vertical flow filtering technologies, and land application. Each section includes a brief introduction, a description of the technology, a review of performance information, an overview of design and management considerations, a brief summary and a list of references/links to additional information.

Holding Ponds

Introduction

Holding ponds (also called sedimentation ponds, containment ponds, settling basins or catchbasins) could be considered the first line of defense for treatment of livestock wastewater runoff. They are designed to remove total suspended solids and allow for flow control prior to any secondary treatment through other means. Suspended solids removal is critical for reducing nutrients from the wastewater and is achieved by solids settling. In climates where rates of evapotranspiration are high, a holding pond may be all that is required to prevent the pollution from entering streams and waterways. However, in cooler climates a holding pond is often required to allow for spring runoff collection and discharge control into further treatment barriers.

Description

Holding ponds are constructed earthen storage basins designed for the temporary storage of wastewater. They generally require a constructed liner either of compacted clay or a synthetic material to provide protection against leakage. Their dimensions are a function of the volume that they are required to store. At a minimum, holding ponds generally require emptying yearly, but in some locations, more frequent emptying may be required.

Performance

The performance of holding ponds for improving runoff water quality can vary widely depending on location, design and holding time. A study in Iowa found that settling basins treating runoff from a feedlot reduced total solids by 65%, TKN by 84% and TP by 80% (USDA-NRCS 2006). At a research site in Ohio, settling basins had removal rates of 44-49% for total solids, 22-35% for organic nitrogen, 26% for BOD and 21-30% for TP (Edwards et al 1983; Edwards et al 1986). Inch (1999) recorded average removal efficiencies in a holding pond upstream of a constructed wetland in Alberta of 73% for TSS, 85% for TKN, 84% for NH_3-N, 74% for BOD, and 11% for TP during one season. However, at a dairy farm in Ontario, Kinsley et al (2013) recorded lower reduction efficiencies in a facultative pond: 42% for TSS, 23% for TKN and 14% for TP.

Nylen and Reedyk (2013) documented the chemical composition of wastewater over two years in 11 holding ponds designed for capturing runoff water from livestock wintering sites. The study was not designed to assess the performance of the ponds in reducing concentrations from runoff, but rather to characterize the water quality of the ponds to help inform secondary treatment options. The water quality of the ponds varied throughout the open-water season, but generally contaminant concentrations (other than salts) decreased from spring to fall.

Typical water quality of holding ponds capturing livestock wintering site runoff

Parameter	Concentration (mg/L)		
	Minimum	Maximum	Average
TP	0.1	56.4	10
TKN	0.4	244	50
TSS	<5	2550	242
NH_3-N	<0.05	88	17
BOD	<5	710	112

Source: Nylen and Reedyk (2013)

Design Considerations for Holding Ponds

Holding ponds are designed to store a specific volume of runoff that is estimated from precipitation data, drainage area and runoff coefficients. Where holding ponds are required by regulations, the minimum storage volume requirement will be identified in the regulations. In other cases, the storage volume requirements will be a function of the treatment requirements and the percentage of annual runoff that the basin is expected to capture. As the water can be very high in nutrients, pre-treatment of the holding pond water prior to release may be required to mitigate the risk of polluting receiving waters. If no treatment occurs prior to the release, the water contained is often land-applied as a fertigation treatment.

Design considerations must include the following:

- Area required
- Sizing and Shape
- Volume of runoff and sediment load
- Precipitation (short term high intensity events)
- Slope
- Frequency of basin cleaning
- Basin outlet
- Management strategy
- Soils and surficial geology

In general, siting of holding ponds will be limited to hydraulically secure soils and will have associated minimum setbacks from water bodies and groundwater wells. Consideration must be given to settling characteristics of the solids in runoff (e.g. settling velocity, particle size distribution) and to the volume of runoff and sediment load to determine the required storage volume needed to achieve appropriate detention time in the pond (Gilbertson and Nienaber 1973; Lott et al. 1994). Side slopes of the holding pond should not be too steep otherwise eroded soil will fill the basin. Generally side slopes range from 2:1 to 4:1 depending on the jurisdiction (Gilbertson et al. 1979; Ontario Ministry of Agriculture, Food and Rural Affairs 2014; Alberta Agriculture and Rural Development 2012; USDA-NRCS 2006). Most jurisdictions require a liner of some sort (compacted clay or synthetic) to limit infiltration through the bottom. Most holding pond system failure is attributed to poor design, including inadequate storage capacity and high bed slopes that do not promote deposition of sediment (Lott et al. 1994).

Holding Pond Management

Holding ponds require routine maintenance and monitoring to ensure they continue to function as designed. Monitoring includes visual inspections for erosion and damage from wildlife, as well as water level monitoring to ensure sufficient freeboard exists to capture precipitation events. Maintenance includes periodic sludge removal and repair of berms from animal burrowing or other damage.

Summary

Holding ponds are a good first line of defense for treating wintering site livestock runoff. They are a very important first treatment step in that they allow for primary sedimentation and allow for control of release to secondary treatment options. Sizing for holding ponds depends on the secondary treatment operation and when flow will be released. If secondary treatment systems are operated year round, holding ponds may be designed for smaller volumes of runoff. However, if secondary treatment systems are only run seasonally when optimal conditions exist, then the holding pond may have to be sized to hold all the snowmelt runoff from the livestock wintering site.

Note

Where they exist, refer to provincial guidelines on design and construction of holding ponds.

Check federal and provincial environmental regulations prior to any construction.

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Holding Pond *In Situ* Treatment

Introduction

There are few studies focused specifically on *in situ* treatment of wastewater in livestock runoff holding ponds, likely due to the cost prohibitive nature of the treatment. Municipal wastewater treatment options are effective but difficult to adapt economically for livestock wastewater holding ponds. However, some physical, chemical and biological treatment options have been studied to assess their applicability to livestock wastewater. Examples of studies on aeration and chemical coagulation as well as the use of floating plant treatments were identified in the review.

Aeration

Description

Aeration is used in wastewater treatment plants to promote the activity of oxygen-using bacteria to aid in the removal of nutrients and organic matter. The bacteria consume nutrients and organic material in the wastewater and convert them to carbon dioxide, ammonia, new cells and other waste material that settles to the bottom. Typical aeration systems for small ponds consist of either a surface aerator (mechanical or pump and spray) or a compressor and an air-line with a diffuser that is submerged near the bottom of the aerated pond (Associated Engineering 2014).

Performance

McGhee et al. (1973) found that aeration successfully treated feedlot runoff in laboratory studies. In trials ranging from 1-8 days, TSS and BOD removals ranged from 66-82% and 69-91%, respectively. In a bench-scale trial of feedlot runoff, after 7.8 days of aeration, Riemersma (2001) recorded average removals of 59% for TSS, 95% for BOD, 52% for TKN, 71% for NH3-N and 40% for TP from the original effluent concentration on day 1. However the controls also had reductions of 32% (TSS), 53% (BOD), 30% (TKN), 54% (NH_3-N) and 33% (TP) from the initial concentrations on day 1. When the aeration was applied in a field-scale setting, the treatment was less effective. During three 30-47 day batch trials, TSS increased in two of the trials and was reduced by 49% in the third. Total phosphorus and ammonia also increased in one of the trials, and only minor reductions (<25%) in TP and NH_3-N were found in the others. The reduced treatment efficiency at the field-scale was thought to be related to the course-bubbler air diffuser which did not allow sufficient oxygen transfer (Riemersma 2001). In the French alps, a study on an aerated settling tank and vertical flow reed bed used to treat dairy effluent showed that the combined effect of settling and aeration in the aeration tank reduced concentrations in runoff by 41% for BOD, 53% for TSS, 39% for TKN, 38% for NH_3-N and 9% for TP (Merlin and Gaillot 2010).

Coagulation

Description

Coagulation is a process that is used in wastewater treatment to promote the settling of suspended solids. It is a physical-chemical process in which the addition of a chemical constituent (often aluminum sulphate or iron chloride) combined with mixing promotes the development of a chemical floc that can eventually settle to the bottom of the holding pond. A disadvantage of using chemical coagulants is the requirement for safe chemical handling. The coagulant can be created *in situ* through a process known as electrocoagulation. In this process, the aluminum or iron ions are generated when an electrical current is passed between an aluminum or iron anode and a cathode (Chen 2004).

Performance

In a laboratory study McGhee et al. (1973) found that aluminum and iron salts effectively reduced TSS in feedlot runoff water by 97% and 98% respectively; however, the dosages required ranged from 2300-2500 mg/L of coagulant and they concluded that it would be cost prohibitive to treat large volumes of runoff. Similarly, Riemersma (2001) completed laboratory-scale trials on effluent from a feedlot in Alberta and achieved an 88% reduction in TSS with a 1525 mg/L $FeCl_3$ treatment but also concluded that coagulation was not economically feasible because of the large amounts of chemical required and the energy required for adequate mixing. There are some examples in the literature of the use of electrocoagulation for treating various agricultural wastewaters (e.g. Laridi et al. 2005; Asselein et al. 2008; Thapa et al. 2015) but these are all at laboratory scales and the technology appears to be in its infancy.

Floating Plant Treatments

Description

Biological treatments using floating plants and algae have shown promise as treatments for domestic and agricultural wastewater (e.g. Zirschky and Reed 1988; Dalu and Ndamba 2003; Sooknah and Wilkey 2004; Zimmo et al. 2005; Xian et al. 2010). The basic idea behind floating plant treatments is that not only do the plants take up nutrients which can then be removed via harvesting of the plant material, but the root masses provide surfaces for biofilms to grow and enable bacteria to convert organic matter into inorganic nutrients that can be used by the plants and by the organisms themselves. Floating plant treatments are often suggested as suitable low-cost treatment systems yet there are few examples of farm-scale applications.

Performance

Zimmo et al. (2005) achieved modest reductions in BOD, N and P concentrations of high strength domestic wastewater in a pilot-scale study of duckweed and algae based treatments. The system included a series of 4 cells for each treatment. After the first treatment cell, the BOD concentration of the influent was reduced by 46-50%, and that of total nitrogen and total phosphorus by 14-25% and 26-28%, respectively. Final concentration reductions after going through 4 cells were 85-90% for BOD, 59-74% for nitrogen and 67-91% for phosphorus. Generally the duckweed based system improved water quality better than the algae based system. Aalerts et al. (1996) showed similar reductions in the concentrations of BOD, TKN and TP in a single duckweed-covered sewage lagoon, although the strength of that wastewater was much lower. Dalu and Ndamba (2003) also recorded improvements in the water quality of two duckweed covered wastewater stabilization ponds. Earlier lab trials focused on the use of duckweed to treat domestic sewage also showed modest improvements and concluded that duckweed could be used to improve performance with respect to BOD, nutrients and suspended solids removals (Vermaat and Hanif 1998; Zirschky and Sherwood 1988). Examples of laboratory-scale studies that evaluated the efficacy of free-floating plants such as water hyacinth, pennywort and water lettuce in reducing contaminants in feedlot water also exist and illustrate similar removal efficiencies as those found for duckweed (Sooknah and Wilkie 2004; Rizzo et al. 2012).

Floating macrophyte beds sometimes referred to as floating treatment wetlands (FTWs), in which emergent plants are grown within a floating artificially constructed material, are another biological treatment option. A lab-scale study on the treatment of swine wastewater using a constructed macrophyte floating bed system showed that after a 35 day treatment period, total nitrogen and total phosphorus were reduced by 80-84% and 88-90%, respectively in the macrophyte bed system versus a 69% and 71% reduction for TN and TP in the controls (Xian et al. 2009). In a bench-scale study with full strength swine lagoon wastewater, Hubbard et al. (2004) calculated removal efficiencies in the root zone of the water column of 43-52% for nitrogen and 34-51% for phosphorus. In a study focused on domestic wastewater, Van de Moortel et al. (2010) illustrated removal efficiencies of 45% and 22% for TN and TP for a floating wetland system versus removal efficiencies of 15% and 6% for TN and TP in the controls. Stewart et al. (2008) determined through a lab scale study that the BioHaven FTWs are capable of removing 10,600 mg of nitrate per day, 273 mg of ammonium per day, and 428 mg of phosphate per day per unit island volume (0.093m^2 by 0.183 m or 1 ft^2 by 0.6 ft thick).

Design Considerations for *In Situ* Treatments

Design criteria that must be considered for *in situ* treatments will vary with the type of treatment; however, a first step should include a characterization of the wastewater. With aeration, the size, depth and volume of the holding pond may influence the type of aerator. Surface aeration using a simple pump and sprayer may be sufficient for shallower ponds (<2 m deep), whereas subsurface diffused aeration may be better for deeper ponds (Associated Engineering 2014). With submerged diffused air systems, fine-bubble diffusers are more effective in transferring oxygen than coarse bubble diffusers (Boyd 1998); however, the diffusers are prone to clogging and may require more maintenance. Some studies suggest that intermittent aeration, using a one-hour on one-hour off cycle would improve performance and decrease energy costs (Associated Engineering 2014).

Coagulation requires a system to mix the coagulant and to circulate the chemical throughout the pond to promote flocculation. In small water supply ponds this has been achieved by using a pump coupled with a sprayer, an aeration system, or a boat motor to circulate the slurry throughout the pond. Consideration must also be given to safety requirements for chemical handling and application. Duckweed-based treatment systems require a method to periodically harvest the duckweed. In small ponds this has been achieved using a boom to move the duckweed to the edge and then manually netting or scooping the duckweed. Floating macrophyte beds require circulation of the water through the root zone of the plants, and are therefore often combined with an aeration system.

Management Considerations for In Situ Treatments

Sludge removal becomes important with increased solids settling resulting from *in situ* treatments, particularly if coagulation is used. For duckweed treatments, the duckweed crop should be managed such that the crop density covers the pond surface but still provides enough room to accommodate further growth. Floating treatment wetlands may require periodic harvesting and/or replanting as well as protection of the plants from predation.

Summary

Biological treatment options of floating plants may be the most cost effective *in situ* treatment options for wintering site wastewater holding ponds, but there is a lack of farm-scale study on these options. Aeration can be implemented relatively cost-effectively, and the incremental improvement in water quality from aeration should improve the efficacy of any secondary treatment but like biological treatments, there is limited information on its application for treating agricultural wastewater at the farm-scale. Although chemical coagulation is a proven treatment technology for domestic water and wastewater, its adaptation for treatment of livestock runoff water may be cost prohibitive. If holding pond water is to be released to the environment, it is likely that *in situ* treatment alone would be insufficient and additional treatment would be required prior to release.

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Vegetative Treatment Systems

Introduction

A Vegetative Treatment System (VTS) is an alternative technology that reduces nutrients and pathogens in livestock wastewater. A VTS can be described as a system in which a permanent vegetative area is used for treating runoff by infiltration, settling, dilution, filtration and absorption of pollutants (Toombs 1997).

A VTS is situated down slope from open feedlots and/or settling basins. VTSs have been demonstrated to be cost-effective, practical and environmentally safe solutions to handling agricultural wastewater and runoff (Dillaha et al. 1989).

This overview builds on a previous review by Koelsch et al. (2006) on the state of literature for vegetative treatment systems for management of livestock runoff. Most studies were located in the north and mid-western United States, but 5 references to studies located in Canada were found. Some studies reported on multiple sites. The studies were separated into research on vegetated infiltration basins (VIB) and vegetated filter strips (VFS) which are sometimes referred to as vegetated treatment areas (VTA).

VFS and VIB Description

Both VIB and VFS may be described as areas planted to perennial forages or grasses which rely upon the treatment capabilities of the plant material and the soil for removal of potential pollutants (USDA-NRCS 2006). In a VIB all wastewater that enters the vegetative area infiltrates and a subsurface tile drainage system collects the infiltrated water and delivers the discharge to the next treatment component (usually a VFS). In a VFS, discharge water may or may not reach the end of the strip depending on the amount of water, the flow rate and the infiltration rate. By coupling a VIB and a VFS, greater removal rates of contaminants from livestock wastewater are achieved than removal rates from a single system. In both systems pre-treatment of the water in a holding pond will help improve pollutant removal rates. A VFS or VIB that does not incorporate a holding pond allows the runoff from the feedlot to pass directly through the vegetation.

Performance

In North America, a significant amount of research has been conducted on the use of VTS for treating livestock runoff water, particularly in the United States. Mean concentration reductions are summarized separately for Canadian examples (n=12 sites, all VFS) and from VFS and VIB systems from other regions (n=35 sites and n=6 sites, respectively). Studies that only provided summarized results of average reductions for several sites were weighted according to the number of sites included in that review. More detailed discussion of the Canadian examples follows. All studies from which data were extracted are listed in the reference section.

Average concentration reductions from vegetative treatment systems

	Average Concentration Reduction (%)				
	TSS	TKN	NH_3-N	BOD	TP
VFS (Canadian sites)	88	83	91	58*	71
VFS (other regions)	74	64	56	62	54
VIB (other regions)	79	80	81	77	83

*Results from one study and represent average of 5 sites (Toombs 1997)

Variations in treatment efficacy are related to differences in vegetation, slope, soil types, size of filter strip and influent solids concentration. Some studies achieved concentration reductions in excess of 90% for some parameters (Koelsch et al. 2006); however, the median concentration reductions in the reviewed studies were generally in the 65-80% range. Although some studies reported concentration increases following flow through vegetated treatment systems, the systems were effective in reducing total loads (e.g. Komor and Hansen 2003). Although VTSs are effective in reducing total nitrogen concentrations, many studies found increases in nitrate concentrations following flow through VFSs and VIBs (e.g. Anderson et al. 2013; Bhattarai et al. 2009; Koelsch et al. 2006).

The average treatment efficiency values reported in the reviewed Canadian examples were slightly higher than those found in other regions; however, there were significantly fewer Canadian studies reviewed. In a Quebec field-scale study, Pelletier et al. (2008) recorded removal efficiencies for nitrogen and phosphorus in the 75-99% range but found that during the snowmelt period, the concentrations of nutrients exiting the filter strip were often above the guidelines. The design was meant to be a zero-discharge filter strip, but was inefficient during snowmelt. To deal with this issue, they added small holding ponds to temporarily store some runoff during large snowmelt events (Pelletier et al. 2014). The redesign was effective at reducing the amount of runoff exiting the VFS, achieving zero discharge in one year and allowing only 7% of the flow to exit in the other year. In an Ontario study that included 4 farm-scale vegetated filter strips, Toombs et al. (1997) found that maximum removal rates for all parameters exceeded 93 percent; however, the average removal rates were much more modest with high variability. Total phosphorus removal averaged only 31% and BOD removal averaged 51% (Toombs et al. 1997). The authors contributed this to variability of the runoff quality and the limitations with the grab sample approach to sampling. However, at a fifth site, where the VFS was located downstream of a wetland, the VFS had high removal rates for TSS, N, P and BOD, ranging from 75% - 97% (Toombs 1997). A demonstration study in Manitoba combined the use of a zero-discharge vegetated filter strip and a portable irrigation system to manage wintering site runoff which was stored in a holding pond (Holweger and Timmerman 2014). The study team added the portable irrigation system after finding that the vegetated filter strip could not achieve zero-discharge due to higher than anticipated runoff volumes in some years. No performance data on the VFS were recorded.

Schellinger et al. (1992) conducted a study in the cooler climates of Vermont, U.S. The results showed an insignificant reduction in solids, P, N and bacteria in the surface output and the authors related the poor performance to excessive hydraulic loading rates, resulting in inadequate detention time and preferential flow to subsurface drain tiles. In their discussion, Schellinger et al. (1992) also cited three other studies conducted in cooler U.S. climates (Martel et al. 1980; Walter et al. 1983; Schwer and Clausen 1989) that reported reduced filter strip performance during the winter and spring snowmelt periods for dairy barn waste runoff.

VTS Design

VFS and VIBs are a simple technology; however there are four critical design considerations (siting, sizing, flow properties and plant material) that influence performance. The need for a pre-treatment for solids settling and for temporary storage is also critical to enhance the vegetated treatment system efficacy, especially in cold climates. The addition of tile drains with a VIB adds another element to the design. Tile drainage design will include calculations for depth, spacing and sizing of tile lines. The tiles must be installed deeper than the high water table but above the low water table, to prevent year round water flow from the drainage system

Design considerations must include the following:

- Siting
- Sizing.
- Sheet Flow
- Plant materials
- Slope limitations
- Discharge control
- Pre-treatment/settling basin

Siting

Placement of VTS must be carefully considered to avoid any negative environmental impacts to surface and groundwater systems. Risk assessments should be completed to evaluate any potential connections to ground water and surface water. A risk assessment should also be conducted to evaluate the risk of odour nuisance. Some sites may be unacceptable if certain features such as slope, area, high soil nutrient levels, geological features or proximity to private and public water systems are not appropriate.

Factors to consider when siting a VFS or VIB:

- Site selection should include evaluation and consideration of soil types, location of wetlands, surface water, streams, prevailing wind directions, depth to ground water (regional water table maps, well logs), geological features, wells and septic systems, topography, flood plains, proximity of buildings, roads

- Site selection must include an assessment of the soils to ensure they have acceptable infiltration rates
- Sites with low slopes are preferable to promote sheet flow and prevent channel flow.

Sites that are unacceptable for a VFS or VIB would include:

- slopes greater than 8-10%,
- less than 1 acre of land available for the VFS per acre of feed lot surface,
- high soil P levels.
- geological features such as shallow fractured or exposed bedrock, drainage wells,
- less than 30 m to a private well or 300 m to a public water supply.

Sizing

Two approaches are commonly used for sizing the strip width of the VFS. One approach involves conducting a nutrient balance between the nutrients in the runoff and the nutrients harvested by the plant material. The other approach is to conduct a water balance where the rate of runoff from the feedlot is matched with the infiltration rate of the land area used for the VFS. To conduct the nutrient or water balance many things must be determined such as runoff volume, mass of nutrients, soil infiltration rates, runoff rates, etc. However, a quick and easy estimate for size is to use the ratio of vegetative filter strip area to feedlot drainage area. A ratio > 2 generally ensures more consistent removal rates and more than 50% trapping (Koelsch et al. 2006).

Slope

Recognizing slope limitations is critical to the design of VFS and VIBs. Minimum slope of 1% and maximum of 5% are defined as the optimum slope ranges for design of a VTS (USDA-NRCS 2006).

Sheet Flow

Flow is another important factor when designing a VFS. Flow should be uniformly distributed across the VFS area so that infiltration is maximized, flow velocity is reduced and settling of suspended particles is encouraged.

Plant materials

Plant material selection is a critical factor for VFS design. Forages or other crops should be chosen for their tolerance levels to local climate, flooding and saturated soil conditions and salt concentrations. For removal of nitrate N, at least 50% of the cool season species should be deep-rooted and legumes must all be deep rooted (≥ 1 m). The age of vegetation also influences the infiltration capacity; older vegetation seems to have better infiltration capacity, consequently improving the removal of soluble contaminants (Schmitt et al. 1999; Udawatta et al. 2002). It is also important to plant a dense and diverse vegetative strip to ensure maximum growth and nutrient removal throughout the year.

Pre-treatment

For VTSs and especially for those situated in cooler climates, a pre-treatment settling basin is strongly recommended to collect spring runoff to allow for control and timing of release into the vegetative treatment area during runoff and freeze thaw cycles. A pre-treatment basin also promotes solids settling which will minimize solids accumulation at the front end of the vegetated area and will minimize vegetation damage and the potential for channelized flow paths in the VTS.

Discharge Control

Providing a mechanism to allow control the quantity of water routed through the VTS will help maximize the potential to reach performance targets. Controlling the time of release of liquids from a setting basin ensures appropriate volumes and time for treatment.

For more detailed design information, refer to Vegetative Treatment Systems for Open Lot Runoff, (USDA-NRCS 2006) and Vegetative Filter Strips System Design Manual (Ontario Ministry of Agriculture, Foods and Rural Affairs 2006).

VTS Management

Proper management is critical to ensure performance is meeting expectations and to enhance the longevity of the system. Critical management issues include management and harvesting of the vegetation, managing and tracking the nutrient concentrations, ensuring sheet flow is occurring and controlling the release of runoff in to the VTS.

Treated tile drainage water from the VIB should not be directly discharged to surface water. It should be further treated.

Summary

A VTS is a good option for the treatment of confined livestock wastewater. More research is required in cooler climates where a freeze thaw cycle exists. Siting, sizing, sheet flow, plant materials, slope limitations, discharge control, and pre-treatment/settling basins are the most important factors to consider when designing a vegetative treatment area. In cooler climates where runoff from the containment area occurs during snowmelt, it is especially important to incorporate a storage basin prior to the VFS to help control the amount of discharge. The basin does not need to capture all the runoff, but should be sized to capture a 10 year 1 hour storm runoff volume so that storage can occur during periods where runoff is exceptionally high (e.g. quick melt, rain-on-snow).

Note

Where they exist, refer to provincial guidelines on design and construction of vegetative treatment systems.

Check federal and provincial environmental regulations prior to any construction.

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Constructed Wetlands

Introduction

A constructed wetland can be described as an engineered system designed to mimic the nutrient cycling and biological processes that occur in a natural wetland in order to filter and remove nutrients, sediment and other pollutants from a wastewater source (Miller et al. 2012; Kadlec and Knight 1996). Numerous studies have been conducted on the potential for constructed wetlands to treat wastewater from agricultural livestock operations, although the majority of these studies have focused on wastewater from dairy operations.

Constructed wetlands reduce pollutant concentrations through a combination of physical, chemical and biological mechanisms. Sediment and other particulate matter can settle out of the water while the plants and microorganisms create an environment that allows for transformation and utilization of nutrients. Constructed wetlands can also help increase biodiversity by providing habitat for insects, birds and wildlife.

This overview builds on previous reviews of constructed wetlands used for treating livestock wastewater in cool or cold climate regions (Knight et al. 2000; Cronk 1995; Vyzmal 2007; Harrington and McInnes 2009; Healy and O'Flynn 2011) by adding a specific focus on studies conducted in Canada. More than 10 studies from Canada were documented; the majority of the Canadian studies occurred in eastern Canada although some studies were conducted in the prairies as well.

Constructed Wetland Description

There are two main types of constructed wetlands that have been used for treating livestock wastewater: surface flow (or free water surface) and subsurface flow, each of which can have several sub-types or variations in design (USDA-NRCS 2009). Surface flow (SF) systems have a free water surface exposed directly to the atmosphere and generally have a combination of shallow and deep zones. The shallow zones have rooted aquatic plants or floating mats of aquatic plants distributed throughout while the deeper zones are often plant free, although some deep zones may also have floating aquatic plants. Subsurface flow (SSF) systems have a layer of porous media such as gravel, sand or rock through which water flows horizontally below ground-level. Rooted emergent plants are often planted throughout the gravel bed. There are also examples of vertical flow sub-surface wetlands where wastewater trickles vertically through porous media (e.g. Merlin and Gaillot 2010) and floating treatment wetlands where the plants are rooted in a floating mat (e.g. Hubbard et al. 2004; Van de Moortel et al. 2010).

A constructed wetland is typically only one component of a larger treatment system. Usually a settling basin first captures the wastewater and allows for some initial pre-treatment. Treatment systems often contain a series of wetland cells after which the discharge from the last wetland cell flows over a vegetated area prior to general release into the environment. In some jurisdictions, the effluent from constructed wetlands is not permitted to be discharged to a surface water body and must be land applied (USDA-NRCS 2009).

Constructed Wetland Performance

Field-scale studies throughout the United States, Canada, Europe and the United Kingdom have documented treatment efficiencies for constructed wetlands receiving wastewater from livestock facilities. The majority of the studies are from dairy operations; however, dairy wastewater is similar, and in fact is often higher in strength, particularly in BOD, than runoff from cattle wintering sites. Treatment efficiencies for different types of constructed wetlands used for treating livestock wastewater have been summarized in various reviews (Cronk 1995; Pries et al. 1996; Knight et al. 2000; Vyzamal 2007; Harrington and McInnes 2009; Healy and O'Flynn 2011). Many of the constructed wetland systems studied were surface flow wetlands, which are generally recommended for livestock wastewater over sub-surface flow wetlands due to the relatively high suspended solids concentrations in livestock wastewater and the potential for plugging in SSF wetlands (USDA-NRCS 2009). This summary focused on field scale free water surface flow systems treating livestock or dairy wastewater in cool or cold climate regions. Mean concentration reductions are summarized separately for the Canadian studies (n=13) and for other regions combined (n_{max}=158). For the other regions, studies that only provided summarized results of average reductions for several sites were included in the analysis in two ways: first by weighting the results according to the number of sites included in the review, and second by treating the results as a single entry, since it was not possible to determine if a site was included in more than one review. More detailed discussion of the Canadian examples follows. All studies from which data were extracted are listed in the reference section.

Average concentration reductions in horizontal surface flow constructed wetlands

	Average Concentration Reduction (%)				
	TSS	TKN	NH_3-N	BOD	TP
Canadian Sites	66	65	80	81	55
Other Regions (weighted)	61	45	58	75	55
Other Regions (unweighted)	81	55	71	81	66

Treatment effectiveness can be variable and will be impacted by design and operation. Werker et al (2002) indicated that comparisons among studies are difficult because so many factors influence treatment effectiveness and that there is a need for the development of reference biological and hydrological indicators to allow better understanding of how different engineered designs perform. Some studies have achieved concentration reductions for some parameters in excess of 95% (e.g. Smith et al. 2006; Jamieson et al. 2007; Mustafa et al. 2009; Forbes et al. 2011; Newman et al. 2000) including over winter operation (Smith et al. 2006). However, on average, concentration reductions in the reviewed studies were generally in the 60-80% range. The range of treatment efficiency values reported in the reviewed Canadian examples was similar to that found from individual studies in other regions and in previous reviews of constructed wetland performances.

The TSS removal of the reviewed Canadian studies ranged from -63 to +97%, with a median reduction of 75%. Poor solids removal was evident in two Canadian studies (Inch 1999; Inch unpublished data; Riemersma 2001), but neither of these designs had a deep water component in the wetland cells to allow for settling of sediment. In the first two study years Inch (1999) documented reductions in TSS, but in the following two years (Inch unpublished data) TSS increased significantly in the effluent of the wetland cells.

Most of the Canadian studies reviewed had relatively good nitrogen removal, particularly in the form of ammonia, where the concentration reductions ranged from 42-99%. The median ammonia concentration reduction in the Canadian examples was 90%. Fewer studies reported on TN or TKN, but for those that did the removal efficiencies were similar to ammonia, ranging from 44-92%; however, the median reduction was somewhat lower at 63%.

The BOD reductions in the reviewed Canadian studies ranged from 39-99%, with a median reduction of 83%. In the only study that had a BOD reduction of less than 65%, the average concentration of the influent was already very low at 30 mg/L (Pries and McGarry 2002).

Removal of phosphorus in wetlands is generally lower than the removal of other pollutants because there are fewer processes available to remove phosphorus, and over time, removal efficiency can decrease as the wetland becomes saturated with phosphorus and there is insufficient uptake by plants to counteract the continual inputs (Kadlec and Knight 1996). The primary removal mechanism is through formation and accretion of new sediments and chemical precipitation is often required to improve P removal to meet regulatory requirements (Ibarra 2011). Removal rates are typically in the 40-60% range, and often decrease as the wetland ages. In the reviewed Canadian studies, removal rates ranged from 1-95%, with a median concentration removal of 45%.

Surface Flow Constructed Wetland Design

Several criteria must be considered in the design of constructed wetlands used for the purposes of treating wintering site wastewater as these design features will affect performance. The first step should include a characterization of the wastewater as this will influence the sizing of the treatment system. Consideration must be given to pre-treatment needs, the wetland itself and post-wetland discharge. Firstly, runoff must be collected and undergo pre-treatment in a settling basin to allow for the settling of solids. Within the wetland itself, important features to consider include sizing, layout, inflow/outflow structures, plants, and wildlife controls. Lastly, the effluent from the wetland must be discharged according to provincial regulations.

Design considerations must include the following:

- Siting
- Sizing
- Layout
- Inflow/outflow controls
- Plants
- Nuisance wildlife control
- Pre-treatment/settling basin
- Post-wetland discharge options

Siting

Constructed wetlands should be located to avoid any negative environmental impacts to groundwater systems and to avoid risk of inundation from flooding. Risk assessments should be completed to evaluate any potential connections to ground water and surface water. Site topography is an important consideration. Ideally, constructed wetlands should be located downslope of the wintering site and on land that is flat or gently sloping to take advantage of gravity flow and to minimize earthwork costs. For more detail on siting criteria refer to USDA-NRCS (2009). Key considerations in siting a constructed wetland include:

- Soil assessment - evaluating seepage potential and need for clay liner
- Topographic survey - flat or low slopes to ensure earthwork cuts and fills can be balanced, wetland cells should be level side to side and flat or slightly sloping lengthwise
- Flooding risk - placement outside floodplains to reduce risk of inundation
- Proximity to surface water sources - proximity to other surface water systems must be evaluated and considered with respect to post-wetland discharge options. For example, if wetland effluent cannot be discharged to a water body then sufficient land must be available for effluent storage and disposal via land application.

Sizing

Sizing of the wetland treatment system depends on the volume of wastewater that needs to be treated, the amount of time available for treatment, the strength of the wastewater and the desired level of treatment. The USDA (2009) describes two methods for sizing a wetland based on whether or not there is pre-existing information on the influent concentrations of pollutants in the wastewater. The presumptive method is used when no actual information exists on influent pollutant concentrations, whereas the field test method was developed for use when the characteristics of the influent wastewater are known. Important parameters for sizing include estimating the annual influent volume, the influent concentrations of pollutants, the required effluent concentrations of the pollutants, average operating temperature of the wetland, and the number of days that the wetland will be in operation (USDA-NRCS 2009). Consideration should be given to whether the wetland will be operating year-round or only during the growing season as efficiencies may be somewhat reduced with colder temperatures.

Layout

Constructed wetland treatment systems are often made up of several cells, rather than one large cell. Consideration must be given to the length to width ratio of the cells and the inclusion of shallow and deep zones. The length to width ratio for wetland cells should be in the 2:1 to 4:1 range, but can range as high as 10:1 (USDA-NRCS 2009). If the bottom of the wetland cells is sloped lengthwise then consideration must be given to the depth of the water at the outlet, as this will influence the maximum length of the cell. The cells should also contain a series of shallow and deep zones. The inclusion of deep zones helps to evenly distribute the water and adds to the retention time (Boyd et al 2005). The depth of water in the shallow zones should be in the 15-30 cm range, while the deep zones should be at least 1 m in depth in order to discourage rooted plant growth. The deep zones should make up approximately 25% of the surface area of the wetland cell (Boyd et al. 2005). The outside berms should be high enough to allow for accretion of soil in the wetland, ice cover, and temporary high water levels under storm conditions. Typically the berms are about 1 m higher than the operating depth of the wetland with side slopes of 1.5:1 (Boyd et al. 2005).

Inflow/Outflow controls

Inlet control structures are an important design feature to ensure even distribution of the influent into the wetland cells and to control flow rates. Consideration must also be given to whether the wetland will be operating over winter or only during the growing season. Typically, control options include either gated pipe spanning the width of the cell or a deep trench or deep zone across the width of the upper end of the cell. A gated pipe allows accurate distribution of the influent, but can be prone to clogging, and is not suitable for operating over winter.

Outflow controls allow regulation of water levels in the wetland and are critical if operating the wetland over winter so that an insulating ice layer can be created. Stop-log structures or swivel pipes are common structures to control water levels.

Plants

Native emergent herbaceous plants are typically planted in the shallow zones of the wetland cells. Common plants include bulrushes (Scirpus spp.), cattails (Typha spp.), reeds (Phragmites spp.), and rushes (Juncus spp.). The role of the plants in the treatment process is to provide a substrate for the growth of microorganisms that drive the treatment process, to facilitate nitrification and denitrification, to use nutrients and to help filter solids. Harvesting of plants, roots and soil from nearby natural wetlands generally has the greatest success rate for plant establishment in the constructed wetlands. Permits may be required to remove plant material from natural wetlands. Commercial supplies of native plants are another good option.

Wildlife control

Wetland cells should be protected against wildlife that might impact the operation of the wetland. Galvanized metal wire screening can be inserted vertically into the outer embankment to prevent muskrats from burrowing into the wetland. Electric fencing along the perimeter can be used to deter moose from grazing in the wetland.

Pre-treatment

Wintering site runoff should be pre-treated before release into a constructed wetland. A catch basin will allow for solids settling and other pollutant reductions. The degree of pre-treatment will depend on the strength of the wastewater and could range from a simple catch basin or settling pond to various forms of treatment within the catch basin (see in situ section).

Post-wetland discharge options

Consideration must be given to how and where the wetland effluent will be discharged. Some jurisdictions do not allow discharge to a receiving water body. In these cases, the discharge can be routed through a permanently vegetated area (e.g. grassed waterway) and allowed to gradually infiltrate, or be stored in another pond and used for irrigation purposes.

Constructed Wetland Management

Proper management is critical to ensure performance is meeting expectations and to enhance the longevity of the system. Critical operation and maintenance issues include water level management, plant replacement and/or harvesting, periodic excavation of sediment and plant litter, monitoring the influent and effluent water quality, inspecting the embankments and repairing any damage, and controlling the inflow and outflow rates. If the wetland is operational over winter, water levels in the cells should be raised prior to freeze up to allow buildup of an insulating layer, and consideration must be given to how the effluent is managed over winter.

Summary

Constructed wetlands are a good option for the treatment of livestock wintering site wastewater. A significant number of studies have been conducted and the vast majority illustrates effective treatment. A number of resources exist that provide information on design criteria; however, because considerable variation in treatment efficiencies is reported, it is recommended that some form of monitoring and reporting be required when the technology is used for treating wastewater.

Note

Where they exist, refer to provincial guidelines on design and construction of constructed wetlands.

Check federal and provincial environmental regulations prior to any construction.

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Vertical Flow Filtering Technologies

Introduction

A number of different filtering technologies have been evaluated for their potential to treat various forms of wastewater, most commonly domestic wastewater. Some of these technologies have been studied, primarily at the laboratory or bench scales, for their application to livestock wastewater. In some cases, different filtering technologies are used in combination. For example, a field-scale combined sand and woodchip filter was tested in Alberta and Saskatchewan for treating wintering site wastewater (Reedyk et al. 2014). Similarly, a field-scale passive filter system containing a graded and washed sand cell, followed by a woodchip cell, then a special limestone mining slag cell for P removal, and finally a peat moss cell for pH adjustment is currently being monitored in Manitoba (L. Braul, Agriculture and Agri-food Canada, personal communication). Much of this work is still in the investigative stage and is untested at the farm scale. In many cases, design features are still being tested for their impacts on removal efficiencies.

Intermittently Dosed Sand Filters

Description

Sand filters have a long history of being used to treat septic tank effluent and a few studies have been undertaken to test their potential for different forms of agricultural wastewater, including livestock feeding site runoff, dairy, and poultry processing wastewater. Typically sand filters consist of a bed of graded sand overtop a layer of gravel with an underdrain. The most common form of sand filter is the intermittent sand filter (ISF) in which the surface of the bed is dosed intermittently with wastewater that percolates downward in a single pass through the sand to the bottom of the filter. In most cases the filter will have an impermeable barrier such that the effluent can be collected and further treated or land applied. Some filters are designed as multiple pass systems where the effluent is re-circulated through the filter prior to be being released. Other filter material, such as peat, gravel, recycled glass chips, and woodchips, have also been used as filtration media in intermittently dosed filters used for treating domestic wastewater.

Performance

There are a few studies that document the use of sand filters for treating livestock wastewater. In Ireland, researchers tested the performance of laboratory scale ISFs to treat dairy wastewater (Rogers et al. 2005; Healy et al. 2007). In one study they achieved >99% removal of TSS and an 86% reduction in TN using an intermittently dosed recirculating sand filter loaded at $10L/m^2/d$, although some of the influent nitrogen was converted to nitrate (NO_3-N) resulting in a 33% increase in NO_3-N concentrations in the effluent (Healy et al. 2007). Surface ponding occurred when the hydraulic loading rate was increased. Rogers et al. (2005) examined the potential for P removal in a single pass ISF and found >80% removal of PO_4-P, but found that the adsorption capacity of the sand decreased over time. In Ohio, Kang et al. (2007) found >98% BOD removal using a laboratory scale ISF dosed with turkey processing wastewater at hydraulic loading rates of 66-132 L/m^2/d. Reedyk et al. (2014) tested the performance of two field scale single pass ISFs for treating cattle wintering site runoff in Saskatchewan and Alberta. At the Saskatchewan site, with a hydraulic loading rate of 145 L/m^2/d the average removal rates for TSS, BOD, TKN, NH_3-N, and TP were 80%, 87%, 38%, 69% and 24%, respectively. Lower removal rates were obtained at the Alberta site but the influent quality was much worse, resulting in clogging of the filter. Surface clogging of sand filters is a common problem and is often caused by high hydraulic and organic loading rates that lead to development of bacterial growth at the surface (Leverenz et al. 2009).

Woodchip Filters

Description

Woodchip filters have been studied quite extensively as a means of reducing nitrate pollution from tile drainage. They were also adopted to remove nitrate from septic tank effluent. Their use in treating livestock wastewater is less common but some examples exist. Denitrifying woodchip filters are usually constructed in a buried trench so that the environment is anaerobic and water flows horizontally along the length of the filter. Vertical flow woodchip filters with a design similar to a sand filter have also been constructed with a layer of woodchips overtop a layer of gravel and a drain with the influent dispersed on the surface and allowed to flow vertically downward.

Performance

Very few examples of woodchip filters designed for treating livestock wastewater exist. Three examples of vertical flow woodchip filter field studies were found. Ruane et al. (2011) tested a farm scale woodchip filter (HLR of 30 L/m^2/d) to treat dairy wastewater and achieved removal rates of 66%, 86% and 57% for COD, TSS and TN, respectively. These rates were up to 30% lower than what they found in a preliminary bench scale study (Ruane et al. 2012). The woodchip filter studied by Ruane et al. (2011, 2012) was designed to be aerobic, and not specifically a denitrifying bioreactor and was followed by a sand filter. Reedyk et al. (2008, 2014) also tested woodchip filters at both bench and field scales. In their field scale study (HLR of 142 L/m^2/d) they documented average removal rates for BOD, TSS, TKN, NH_3-N and TP of 36%, 45%, 36%, 73% and 15%, respectively (Reedyk et al. 2014). The removal rates in the bench scale study (Reedyk et al. 2008) were similar or slightly higher for most parameters except BOD. The woodchip filter in this study was initially meant as a polishing filter for removing nitrate after a sand filter, but when the sand filter clogged, the woodchip filter was operated on its own (Reedyk et al. 2014). Ergas et al. (2010) evaluated two bioretention systems that incorporated aerobic and anaerobic components for control of nutrients and other pollutants from agricultural runoff. Their field scale trials tested the efficacy of both woodchip-based and sulfur-based denitrification substrates. During their high-loading rate trials (HLR of 300 L/m^2/d) which were run with effluent typical of livestock runoff they achieved removal efficiencies of 48% for BOD, 69% for TSS, 66% for TP, and 65% for TN (Ergas et al. 2010). Pelletier et al. (2014) tested a field-scale woodchip bioreactor as a pre-treatment to wastewater runoff from a wintering site entering a vegetated filter strip. In the first year of study, the reactor achieved removal efficiencies of 88% for TSS, 74% for NH_3-N, 73% for TN and 68% for TP. However, in the second year of operation, the filter was either saturated or was affected preferential flow, as no removal was observed.

Filter Mounds

Description

A filter mound is essentially a drain field that is raised above the natural soil surface and filled with some type of filter media (e.g. sand, woodchips, bark). Wastewater is distributed into the mound through a pressure distribution system and moves vertically through the filter material, continuing downwards into the soil. A design guide is available through the University of Minnesota Extension Service (Schmidt et al. 2007).

Performance

Rathbun et al. (2012) tested the efficacy of four different filter media in a field scale filter mound at a dairy farm in Michigan. The filter mound was dosed at a hydraulic loading rate of 13.5 $L/m^2/d$ and the different media included hardwood bark, aerated hardwood bark, hardwood wood chips, and Styrofoam chips. The hardwood bark treatment (both aerated and unaerated) was most efficient, achieving removal rates in excess of 90% for TP, NH_3-N, TSS, and E. coli bacteria. Wood chips were less effective, and Styrofoam chips provided essentially no treatment.

Multi-Soil-Layering Systems

Description

Multi soil layer (MSL) systems are layered systems containing aerobic layers of permeable material like zeolite or perlite and anaerobic soil mixture layers that are arranged in blocks throughout the depth of the filter. The soil blocks often contain other materials like activated carbon, granular iron or wood chips to enhance nutrient removal. Wastewater is applied at the surface and allowed to trickle downwards through the layers to a gravel drain.

Performance

MSL systems have primarily been studied in Asia as a means for treating domestic wastewater (e.g. Attanandana et al. 2000; Chen et al. 2007a; Luanmanee et al. 2002; Sato et al. 2011; Latrach et al. 2015; Luo et al. 2014); however, some examples of their use for livestock wastewater exist (Chen et al. 2007b; Chen et al. 2009; Pattnaik et al. 2007). Many of the studies are laboratory scale studies that tested different media in both the soil blocks and the aerobic layers. Recent studies that evaluated the MSL system for treating domestic wastewater achieved fairly high removal rates for many parameters. Latrach et al. (2015) found mean removal efficiencies of TSS, BOD, TN and TP to be 93%, 86%, 78% and 80%, respectively. Similarly, Luo et al. (2014) documented removal efficiencies for COD, TP and TN in the range of 90-95%, 92-94% and 59-64%, respectively. The results of an unpublished study on using MSL systems for treating livestock wastewater are described by Chen et al. (2009). In this study, the reported removal rates for TSS, BOD, ammonia and phosphate ranged from 95-97%, 96-99%, 75-99%, and 80-99%, respectively, at a hydraulic loading rate of 220 $L/m^2/d$ (Chen et al. 2009). Other experiments using livestock wastewater were more variable. Chen et al. (2007b) tested the removal of COD from livestock wastewater in four different MSL systems at a hydraulic loading rate of 250 $L/m^2/d$. Average removal efficiencies were 49-58% over a six week trial. Pattnaik et al. (2007) tested two different MSL systems for their ability to treat dairy wastewater using variable hydraulic lading rates of 178-505 $L/m^2/d$. They found removal rates for inorganic nitrogen were initially high in both systems but decreased over time, ranging from 20-96%. Phosphate removal varied between the two systems, ranging from 64-99% in one and 9-97% in the other. When sucrose and constant aeration was added to both systems, removal rates for both nutrients increased (Pattnaik et al. 2007).

Design Considerations for Filtering Technologies

Key design criteria that must be considered in the design of vertical flow filters include the hydraulic loading rate, the organic load, and the depth, type and uniformity of the filter media. Like other treatment technologies, some form of pre-treatment, including a settling basin, is necessary and a first step should include a characterization of the wastewater as this will influence the sizing of the treatment system. Solomon et al. (1998) provide an overview of some design features and operation and maintenance requirements of intermittent sand filters for domestic wastewater; however, because wintering site runoff can have significantly higher organic loads, lower hydraulic loading rates are likely needed. The effluent from the filter must be discharged according to provincial regulations.

Management Considerations for Filtering Technologies

Maintenance will vary with the different technologies but a key consideration with all is monitoring inflow and outflow to ensure proper application rates and to check for clogging or preferential flow paths. Periodically the filter media may require full or partial replacement. Depending on the type of distribution system used to deliver the influent to the filter, the orifices may require periodic flushing to prevent clogging.

Summary

Vertical flow filtering technologies can provide a means to treat livestock wintering site runoff, but many of these technologies remain in the development/testing stage and insufficient information exists to confidently predict treatment efficacy for livestock wastewater. More field scale studies using wintering site effluent are likely required before these technologies could be recommended as options.

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Livestock Holding Pond Wastewater Irrigation

Introduction

Runoff collected in holding ponds from wintering site confinement areas can be used as an irrigation source for agricultural land. Irrigation methods are generally classified as surface/gravity and pressurized. Both methods can be used in the disposal or land application of livestock runoff from holding ponds. Selection of the method to be used is usually based on criteria such as economic considerations, soil physical characteristics, topography of land, type of crops, availability of skilled labor, and the quality of the water (Feigin et al. 1991). The objective of using livestock runoff for irrigation in most cases is to dispose of the effluent in an environmentally sustainable manner. Maximizing crop production from the irrigation benefit may be secondary, especially in regions where other sources of water are available for irrigation. Considerations for land application include runoff water quality, crop type, potential legal issues, the suitability of land for application, and system design, operation and maintenance (Tyson and Sneed 2011).

Irrigation using livestock runoff water collected from holding ponds may be regulated at federal, provincial or municipal levels in order to avoid or minimize the impact associated with application to the land and surrounding water bodies. The regulations may include the distance of the land application area from surface water, public places and wells, and restrictions on which crops that can be irrigated. Some jurisdictions may require professional engineers for the design of the irrigation system and may also regulate the irrigation system permitted.

Description

There are various types of irrigation systems available to use for effluent irrigation from confined wintering livestock holding ponds, including stationary irrigation big guns, travelling irrigation big guns, centre pivots or smaller component pod based systems.

Stationary Big Gun Sprinkler

Stationary big gun sprinkler irrigation systems are feasible to dispose of effluent including livestock runoff from confined wintering site holding ponds. A pump and a mainline pipeline together with a single large volume sprinkler gun form the main components. The nozzle sizes of stationary big gun sprinkler systems are typically in the range of 25 to 50 mm and they operate most effectively in the pressure range of 551 kPa to 827 kPa (Pfost et al. 2001). Typically, a stationary big gun discharges 21 L/S at a pressure of 620 kPa (Scherer et al. 1999).

Advantages:

- A large flow rate and large wetted area is attained with the system, resulting in less labor required in moving the big gun sprinkler
- Reduced plugging problems due to large nozzles

- Fewer pipes required for the system compared to small sprinkler systems
- System has few mechanical parts
- The system is flexible in terms of land area

Disadvantages:

- Moderate to high initial cost
- Wind may affect effluent distribution on land
- Tendency to over-apply effluent
- Power requirement is relatively high

Traveling Big Gun Sprinkler

A traveling big gun sprinkler is suitable for large areas of land where irrigation is required many times in a year. It is a self-propelled sprinkler system with variable speed capability to control application depths and can cover larger land areas compared to stationary systems. A water-driven winch located on the big gun sprinkler pulls itself on the ground by a cable anchored at the end of the field (Scherer et al. 1999). On some of the smaller models the winch may be driven by a small engine. Above ground aluminum pipe or underground plastic pipe is usually used to convey effluent from holding ponds to the point of attachment in the field (Pfost et al. 2001).

Advantages:

- Fewer plugging problems with large nozzles
- Average labor requirements
- Flexible in terms of land application area

Disadvantages:

- Potential for high application rate is high
- Initial cost is higher than stationary gun
- High Power requirement
- Higher proportion of mechanical parts compared to a stationary gun

Center Pivot Irrigation System

The main components of a center pivot system would include a pump, pump station controls, pipeline, pivot and sprinkler package, and backflow prevention device, if also using the pivot at other times to irrigate with surface or ground water. Due to the relatively high costs of center pivots and the pipeline infrastructure required to supply effluent to the pivot, a center pivot for livestock runoff would typically only be an option if the irrigation system was already in place, and at other times utilizing surface or ground water for irrigation. There are many factors to consider when determining to use a center pivot including odor concerns, water quality, soil conservation and quality, rules and regulations, application rates and application equipment (Kranz et al. 2007). Depending on other project parameters, including topography, distance from holding pond to pivot, overall pipeline layout, and design constraints of the system when using ground or surface water, careful consideration must be taken to determine if a pivot would be feasible. Kranz et al. (2007) also determined the following benefits and potential issues to address:

Advantages:

- A shorter odour production time compared to spreading on land
- More uniform application of nutrients than spreader or tankers
- Application can occur during the growing season
- Ability to apply large volume of material in short amount of time (depending on water deficit, soil type and crop uptake ability)

Disadvantages:

- Higher cost of pivot and infrastructure
- Potential for surface runoff and leaching
- Backflow prevention equipment required, if also using pivot system with surface or groundwater source
- Potential for cross contamination of surface or ground water source

Low-Rate Pod Based Irrigation Systems

Pod based irrigation systems include multiple sprinkler heads on a small diameter flexible pipeline, each encased in a protective rigid plastic pod, which offers protection to the sprinkler when moving the system. A pod based sprinkler system offers a less expensive alternative for irrigation of confined wintering site holding pond runoff compared to a pivot or travelling gun. The system requires a pump, a main pipeline to convey the effluent, and the pod based pipeline and sprinkler head package, which would be selected based on the available land for application, volume of runoff to distribute, type of soil and the crop to be irrigated. Typically, pipelines for pod based systems are installed above ground, and use a smaller diameter of pipe of both high and low density polyethylene, to convey the effluent compared to larger diameter buried PVC pipe typically used for pivots or big guns. Pod based systems were first developed in New Zealand to meet a need for a more flexible irrigation system in the dairy and livestock industry (K-line 2016).

The main pipeline of a pod based system typically has multiple tap off points, allowing for frequent movements of the system thereby increasing the land base available for effluent application. A benefit of a pod based system is the ability to apply smaller amounts of effluent to the land base over a longer period of time, thereby allowing a longer time for the soil to absorb the effluent and thereby reducing the potential for runoff (Monaghan et al. 2010).

Advantages:

- Relatively inexpensive compared to pivot or big gun systems.
- Ability to apply effluent over a longer time period to allow for slow absorption by the soil and a decreased potential for runoff.
- Pod cover provides protective element to the sprinkler head
- Flexible system for many different applications and areas
- Strong but lightweight system and easy to move

Disadvantages:

- Lower application capacity compared to big gun or pivot (would take longer to apply larger volume of holding pond effluent)
- Increased labour requirement to move system
- Potential for plugging
- Solid removal may be required

Design Considerations

Critical design considerations include sprinkler application rate, application depth per irrigation event, and total runoff volume or effluent depth applied annually. Soil infiltration or permeability and the content of solids in the effluent would determine the application rate of the sprinklers (Scherer et al. 1999). If the application rate of the sprinkler is more than the infiltration rate of the soil, or the depth of wastewater applied during an irrigation event is more than the equivalent amount which can infiltrate into the soil, the excess effluent would result in runoff which is often not permitted under regulations. The choice of irrigation system (low-rate versus high-rate sprinkler applications) may be influenced by the total volume of the holding pond and the amount of time available for emptying the pond. Distance and elevation changes from the holding pond to the irrigated land will influence pump and pipe sizing.

Management Considerations

The conductivity of wintering site holding pond water averages around 2300 µS/cm and can be as high as 6500 µS/cm (Nylen and Reedyk 2013). Repeated applications of saline wastewater to agricultural land can affect the physical and chemical properties of the soil as well as crop yield (Ayers and Westcot 1985). Soil conductivity may increase over time as the dissolved salts in the applied irrigation water concentrate through evapotranspiration. Rotating the land that is irrigated will allow rain and snowmelt to leach salts below the root zone. Rotation will also reduce the risk of building up high soil nutrient concentrations. At N and P concentrations ranging from 50-150 mg/L N and 10-50 mg/L P, every inch of irrigation water applied, amounts to application rates of 11-34 lbs/acre N and 2-11 lbs/acre P.

Summary

Land application of livestock wastewater is a good option for treating runoff water from livestock wintering sites; however, because the water from wintering sites can be relatively saline, soil salinity monitoring should take place prior to and after irrigation. Yearly rotation of the land areas that are irrigated will allow for some leaching to occur via snowmelt and rainfall events.

Note

Check federal and provincial regulations regarding irrigation of agricultural lands with wastewater.

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Summary

This review focused on fifteen treatment technologies that have been tested as a means of improving the quality of wastewater derived from cattle handling sites. The specific focus was on technologies suitable for treating runoff water from cattle wintering sites, but information was also extracted from other cattle handling sites, including feedlots and dairies. The technologies were grouped into the three basic categories: holding ponds, including *in situ* treatment options, post holding pond filtering treatments, and land application (Table 1). In most cases, full treatment includes a combination of these technologies where first the wastewater is collected to allow some form of *in situ* treatment, and is then followed by some form of filtering technology.

Treatment efficiencies varied both among and within treatment technologies and in most cases there are examples of both inefficient and very efficient treatments within any one technology. Maximum treatment efficiencies for those technologies where field-scale livestock wastewater treatment examples exist ranged from a low of 24% for TP with aeration to a high of 99% for TSS, NH3-N, TP and BOD with constructed wetlands and vegetated treatment systems (Table 2). Based on the studies reviewed, both constructed wetlands and vegetated treatment systems individually could be reasonably expected to reduce contaminant concentrations on average by 60-80%, with higher efficiencies possible. Furthermore, mass reductions of contaminants would be expected to be higher with both systems as infiltration and evaporation would lead to reduced effluent volumes. With all the technologies, design and management will influence treatment efficiency. As well, many design aspects are site specific and under certain conditions a specific technology's applicability could be limited under high risk scenarios (Table 3).

Although many of the technologies have been tested at the farm scale, limited examples of most suggest that many technologies require regional testing to ensure that they will function well and can be recommended as a best management practice. Of the technologies reviewed, vegetated treatment systems (VTSs), constructed wetlands (CWs), and wastewater irrigation applications had the most examples of studies and applications across the country and are three technologies that are already recommended as best practices in some regions of the country and could be recommended for those regions where they are not currently in use. Certain design features of these technologies may be impacted by regional climatic differences, but in most cases sufficient information exists that will allow for modifications to the designs such that the technologies could be implemented without significant testing. Both constructed wetlands and VTSs have been tested in eastern Canada under year-round operating conditions, and some modifications to initial designs were required to deal with variable melt conditions and/or cold temperature operation (e.g. CW - Smith et al 2006, VTS - Pelletier et al 2014). Although examples of constructed wetland and VTS studies also exist in the prairies, no examples exist of operation of these technologies under harsh prairie winter conditions. In all regions, design consideration for these technologies should be given to:

- determining the operating time frame of the technology as that may impact sizing of many components;

- evaluating whether (extra) storage capacity is required to deal with rain on snow events during spring runoff that would trigger higher than normal amounts of runoff during shorter time frames;
- evaluating whether (extra) storage capacity is required to deal with operation in winter or spring when low temperatures may cause lower treatment efficiencies or require longer residence times;
- identifying whether freeze-thaw cycles may impact inflow and discharge control structures (e.g. Icing up overnight during spring thaw);
- locating the treatment system to take advantage of natural insulating environments (e.g. sheltered areas)
- locating the treatment system to take advantage of gravity, or using wind and solar power to reduce grid power needs
- evaluating risk of salinity increases in drier regions with repeated application of wastewater in VTAs and on irrigated lands.

Some technologies that show promise but have limited farm-scale testing include holding pond floating plant treatments, sand and woodchip filters, and earth mounds. Regional testing of these technologies at the farm scale would fill information gaps, and could provide alternative treatment options relatively quickly.

Table 1: Status of farm-scale research on treatment technologies suitable for confined wintering site runoff

Type	Technology		TSS	TP	TKN	NH4-N	BOD
Holding Pond	Settling/Sedimentation		●+	●+	●+	●+	●+
	Aeration		◖+	◖+	◖+	◖+	◖+
	Coagulation		○	○	○	○	○
	Plants	Duckweed	◖	◖	◖	◖	◖
		Floating Wetland Islands	◖	◖	◖	◖	◖
		Hyacinth	◖	◖	◖	◖	◖
Post Holding Pond Filtering Technologies	Sand Filters		◖+	◖+	◖+	◖+	◖+
	Woodchip Filters		◖+	◖+	◖+	◖+	◖+
	Earth Mounds		◖	◖	◖	◖	◖
	Constructed Wetlands	Horizontal Sub-Surface Flow	◖+	◖+	◖+	◖+	◖+
		Horizontal Surface-Flow	●+	●+	●+	●+	●+
		Vertical Flow	◖	◖	◖	◖	◖
	Vegetated Treatment Areas	Vegetated Infiltration Basin	●	●	●	●	●
		Vegetated Filter Strip	●+	●+	●+	●+	◖+
Land Application	Irrigation		◖+	◖+	◖+	◖+	◖+

● Well Documented
◖ Some Study
○ Limited Study
\+ Canadian examples exist

Table 2: Maximum removal efficiencies (% concentration reduction) of various treatment technologies from farm-scale trials treating livestock wastewater*

Type	Technology		TSS	TP	TKN	NH_3-N	BOD
Holding Pond	Settling/Sedimentation		73	80	85	84	74
	Aeration		53	24	39	38	52
Post Holding Pond Filtering Technologies	Sand Filters		80	24	38	69	87
	Woodchip Filters		88	68	73	74	48
	Earth Mounds		90	90	--	90	--
	Constructed Wetlands	Horizontal Surface-Flow	99	95	96	99	99
	Vegetated Treatment Areas	Vegetated Infiltration Basin	88	93	87	92	80
		Vegetated Filter Strip	99	99	98	99	85

*From studies referenced within this document

Table 3: Post holding pond filtering technologies design considerations*

Design Consideration	High Risk Situations	Low Risk Situations	Potential Concern under High Risk Situations	Potential Mitigation Options for High risk Situations
Depth to groundwater	< 3 m	>15 m	All technologies - potential for groundwater contamination	Treatment cells (wetland/sand /woodchip filters) - use clay or synthetic liner
Distance to private wells \ public water supplies	<30 m / <300 m	>60 m / > 600 m	All technologies - potential for groundwater contamination	Treatment cells (wetland/sand /woodchip filters) - use clay or synthetic liner
Soil type	Coarse textured soils (sands)	Fine textured soils (clays)	All technologies - potential for seepage/ground water contamination	Treatment cells (wetland/sand /woodchip filters) - use clay or synthetic liner
Geological Features	Shallow fractured or exposed bedrock, sink holes, karst materials	No high risk geological features known	All technologies - potential for groundwater contamination	None
Soil Permeability/ Infiltration Rates	< 0.5 cm/hr or > 5 cm/hr	0.5 – 5 cm/hr	All technologies - high risk of groundwater contamination Treatment cells - difficult to maintain water levels in treatment cells	Treatment cells (wetland/sand /woodchip filters) - use clay or synthetic liner

Design Consideration	High Risk Situations	Low Risk Situations	Potential Concern under High Risk Situations	Potential Mitigation Options for High risk Situations
Distance to surface water	<30 m	>150 m	All technologies - potential for surface water contamination	None
Soil P levels	High Soil P levels	Low Soil P levels	VTAs - Contamination of surface waters with dissolved P	None
Slope	>10 %	0-5%	Treatment cells - ability to maintain constant water depth VTAs – potential for erosion, reduction in time available for infiltration	Treatment cells/Vegetated treatment areas should be terraced. Note - more land area will be needed which may increase cost
Area/Sizing	<0.5 ha of land per hectare of feedlot	>2 ha of land per hectare of feedlot	VTAs - little infiltration and large runoff from site	none
Flood Plain	VTS system within 10 yr flood plain	VTS system located outside a 25 year flood plain	All technologies - risk of inundation or damage from flood events	Provide protection from flood events
Pre-treatment	No solids settling	Solids settling	All technologies - overloading and ineffectiveness of technologies	Collect wastewater in settling pond upstream of filtering technology

Design Consideration	High Risk Situations	Low Risk Situations	Potential Concern under High Risk Situations	Potential Mitigation Options for High risk Situations
Inflow control	No flow control and/or channel or concentrated flow conditions in VTAs	Ability to control flow release and create uniform flow	All technologies - need to control inflow rates to maintain desired level of treatment VTAs/Wetland cells – need to ensure sufficient water in treatment cell or VTA to meet requirements of vegetation	Wetland cells – ensure outlet of wetland cell is 15-30 cm higher in elevation than the top soil of the shallow zone in the cell
Discharge Control	No discharge control	Zero or minimal discharge	Wetland Cells- inadequate treatment time, no ability to adjust water levels for winter ice management VTAs - inadequate infiltration rate and inappropriate timing of water release (winter)	Install discharge control or control timing of discharge to summer months

Design Consideration	**High Risk Situations**	**Low Risk Situations**	**Potential Concern under High Risk Situations**	**Potential Mitigation Options for High risk Situations**
Vegetation	Intolerant or sparse vegetation, non-diverse and/or inappropriate vegetation for technology	Dense, diverse vegetation tolerant to climate, salts, ammonia and VTA/wetland cell conditions VTAs – high nutrient uptake, value as an animal feed, high ET rates, long growing season crops, perennials, large root mass and surface area, sod forming grasses Wetlands – emergent and floating vegetation local to the region	Wetland cells – inadequate physical filtration, reduction in potential nitrification/denitrification, increased water temperature VTAs - inadequate infiltration and filtration	Plant appropriate vegetation
Odour Nuisance	Neighbors are <0.5 km, downwind and at a lower elevation than treatment areas	Neighbors are >1.5 km, upwind and at a higher elevation than treatment areas	All technologies - possible odour nuisances	Minimize odour risk by siting treatment areas based on prevailing winds, elevations and wind speed

Design Consideration	**High Risk Situations**	**Low Risk Situations**	**Potential Concern under High Risk Situations**	**Potential Mitigation Options for High risk Situations**
Cold climate conditions	Operate over winter / frozen ground season	Operate over spring and summer season	All technologies – potential for reduced treatment efficiencies VTAs – reduced infiltration, greater amounts of runoff Wetland cells – freezing of cells	VTAs- increase length of treatment system, may require more storage capacity Wetland cells – use water level control structures to manage ice layer and residence times

*Adapted from: USDA-NRCS 2006; Koelsch et al. 2006; USDA-NRCS 2009; Smith et al. 2006.

Appendix I

Literature Search Terms Used:
livestock
cattle
wastewater
runoff
agricultural runoff
effluent
winter
wintering
overwintering
cold climate
temperate climate
feedlot
barnyard, farmyard
feeding operation
fence, fencing, fenced
enclosure
pens
confined
Filtration
biological filter
constructed wetland
reed bed
rock filter
woodchips
vegetated filter strip
vegetative filter strip
vegetative treatment
bioreactor
lagoon
settlement pond
settlement basin
catch basin
treatment, pre-treatment, treating

Example of a search strategy used:
((TITLE-ABS-KEY(**woodchip*** OR **"biological filter*"** OR **"vegetative W/15 treatment*"** OR **"vegetative W/15 filter*"** OR **filtration** OR **"reed bed*"** OR **"ROCK FILTER*"** OR **"CONSTRUCTED WETLAND*"** OR **filter*** OR **"SETTLEMENT POND*"** OR **"CATCH BASIN*"** OR **"SAND FILT*"** OR **bioreactor***)) AND (((TITLE-ABS-KEY(**wastewater** OR **runoff** OR **effluent**) AND TITLE-ABS-KEY(**winter*** OR **overwintering** OR **"COLD W/15 CLIMATE"** OR **"TEMPERATE W/15 CLIMATE"** OR **seasonal** OR **year***) AND TITLE-ABS-KEY(**livestock** OR **cattle** OR **dairy** OR **"AGRICULTURAL RUNOFF"**))))) AND (TITLE-ABS-KEY(**treatment** OR **treating** OR **pre-treatment**))

Appendix II

Information Extraction Template

- Publication Reference
- Location (Country, State/Province)
- Type of Wastewater (feedlot, wintering site, dairy, barnyard)
- Type of Treatment
- Scale of treatment (lab, field)
- Length of Study (hours, days, years)
- Treatment season (seasonal, year-long)
- Water quality parameters measured
- Economic information
- Influent concentrations
- Effluent concentrations
- % Removal