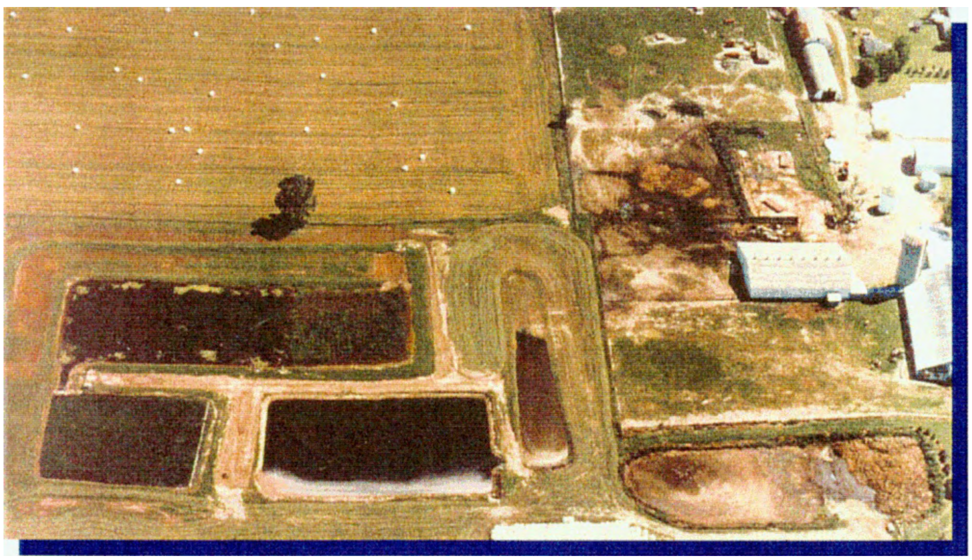
GUIDANCE MANUAL FOR THE DESIGN, CONSTRUCTION AND OPERATIONS OF CONSTRUCTED WETLANDS FOR RURAL APPLICATIONS IN ONTARIO

**Funded by the Canadapt Program
of the
Agricultural Adaptation Council, Ontario**



By Stantec Consulting Ltd
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South Nation Conservation

November, 1999

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Cover Photo: Dignard Dairy Farm Constructed Wetland (see Appendix A).

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Author's Preface

The following manual provides a review of considerations and steps required for the design, construction and operation of constructed wetlands for wastewater treatment in rural applications (i.e. livestock operations, food processing, septic waste treatment, etc.). The information provided herein is to be used by practitioners (i.e. professionals with a working knowledge of geotechnical engineering, hydrology, hydrogeology and wastewater treatment) to provide them with enough detailed information to determine if this application is applicable to their needs and if so, to help them develop, implement and operate a constructed wetland treatment system. The guidelines outlined herein provide a standard system approach for a simple low cost, low maintenance solution. The constructed wetlands discussed in this manual are therefore limited to simple systems such as those found in nature, and do not consider more complex designs such as sub-surface systems and complex mechanical devices.
The design examples used in this manual are therefore based on the simpler loading rates methods. This manual can be used by technical staff in provincial agencies, consulting firms, construction companies as well as potential operators and owners of constructed wetland systems.

1.0 INTRODUCTION

Non-point source (NPS) pollution is one of the North America’s largest sources of water quality problems *(Water National Quality Inventory, 1994)*. Non-point source pollution is caused by polluted surface runoff that flows into rivers, lakes and groundwater. Since the wastewater source is not as obvious as point-source pollution, it can be more difficult to treat and is often over-looked. Agriculture and faulty septic tanks are major generators of non-point source pollution. New on-site treatment technologies such as constructed wetlands and riparian zone management are being used for treatment of non-point source pollution in many rural environments. Constructed wetlands use vegetation in combination with sedimentation, adsorption and biological degradation to treat a variety of wastewater types. They are used for treating landfill leachate, mine drainage, agricultural wastes, septic tank effluent, food processing waste, municipal sewage, stormwater runoff and many other sources. A database compiled by the United States Environmental Protection Agency contains an inventory of over 150 North American wastewater treatment wetlands (*Brown and Reed, 1994*). Although the majority of these systems have been installed in the southern states, sewage treatment wetlands are in operation as far north as the North West Territories.

The use of constructed wetlands for wastewater treatment is not a new idea. Ancient Chinese and Egyptian cultures made use of their pollution abatement potential (*Brix, 1994*). In Europe, experimentation with aquatic plants for removing organic and inorganic contaminants from water began in the 1950's and continues today. Denmark, Germany and the United Kingdom each have about 200 functional sewage treatment wetlands (*Brix, 1994*). Constructed wetlands have been used for sewage treatment in all regions of Europe, even in countries with harsh winters such as Norway (*Jenssen et al., 1994*), the Czech Republic (*Vymagal, 1993*) and republics of the former Soviet Union (*Magmedov et al., 1994*). Constructed wetlands can be found on every continent of the earth except Antarctica.

2.0 TYPES OF CONSTRUCTED WETLANDS

2.1 General Classifications

Constructed wetlands are classified as either *Free Water Surface (FWS)* systems or *Subsurface Flow (SSF)* systems. Any wetland, in which the surface of the water flowing through the system is exposed to the atmosphere, is classified as an FWS system. In SSF systems water is designed to flow through a granular media, without coming into contact with the atmosphere.

Free water surface wetlands can be sub-classified according to their dominant type of vegetation: *Emergent macrophyte*, *Free floating macrophyte*, or *Submerged macrophyte*. Subsurface flow wetlands (which by definition must be planted with emergent macrophytes) can best be sub-classified according to their flow patterns: *Horizontal flow* or *Vertical flow*. A classification system is shown in Figure 1.

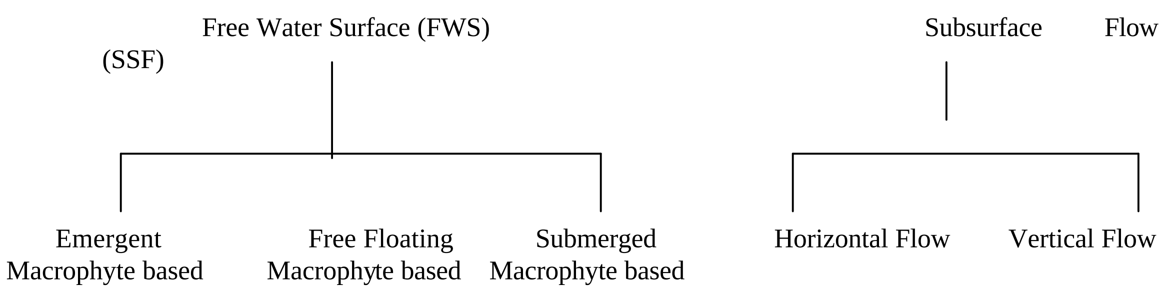

Figure 1 - Wetland Design Categories.

2.2 Free Water Surface Wetlands

2.2.1 Emergent Macrophyte Based Wetlands

Emergent macrophyte based wetlands are the most common type of FWS. They consist of a series of channels and/or basins which are lined with an impermeable material (such as clay) in order to limit infiltration. A layer of soil is provided on top of the impervious material in which emergent macrophytes (such as cattails and bulrushes) are planted. A slow flow rate is applied so that a shallow depth is maintained (*Hamilton et al., 1993*). Settleable solids are removed by sedimentation, which lowers biochemical oxygen demand (BOD) and removes particulate forms of phosphorus and nitrogen from the wastewater. A nutrient rich sludge is then formed on the wetland floor. The macrophytes supply oxygen to the sludge zone through their roots, thereby promoting aerobic digestion of the pollutants by microorganisms. Macrophytes also act as physical supports for microorganisms that help remove pollutants.

2.2.2 Free Floating Macrophyte Based Wetlands

As the name implies, *free floating macrophyte based wetlands* make use of floating plants, such as duckweed and water hyacinth, to remove nutrients and control algae in wastewater. A floating barrier grid is used to support the growth of floating macrophytes and to reduce wind effects, which would otherwise cause the plants to drift. It has been claimed that the floating plant mat blocks out sunlight, thereby preventing photosynthesis and inhibiting algae growth (*Lemna Corporation, 1994*). The plant mat and barrier grid reduce turbulence, allowing suspended solids to settle out more readily. A pontoon boat for harvesting the floating plants from the treatment system is commercially available. It has been suggested that harvesting be done "periodically", depending on climate, nutrient loading and desired treatment (*Lemna Corporation, 1994*).

2.2.3 Submerged Macrophyte Based Wetlands

Submerged macrophyte based wetlands are still in the experimental stage. They have been proposed as final polishing steps following primary and secondary treatment (*Brix, 1994*). Little information is available describing these systems.

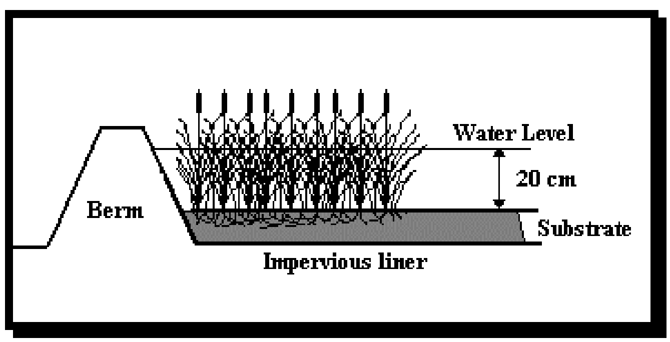

Figure 2 - Profile of Free Water Surface Wetland Cell with Emergent Macrophytes

2.3 Subsurface flow wetlands

Subsurface flow (SSF) type wetlands make use of the same removal mechanisms as FWS wetlands: sedimentation, filtration and microbiological degradation. However, since the wastewater flow is below the surface, it is in continuous contact with the filter media, which in turn provides more surface area for bacterial growth, therefore allowing for higher organic loading rates.

2.3.1 Horizontal Flow SSF Wetland

In *horizontal flow* SSF wetlands, the medium is kept saturated under a continuous wastewater flow. Oxygen is then transferred from the atmosphere into the wetland through the emergent plants.

2.3.2 Vertical Flow SSF Wetland

Vertical flow SSF wetlands are operated as a batch process rather than in continuous flow mode. Wastewater is dosed at timed intervals so that the filter is allowed to drain. Consequently, the system is not always saturated and oxygen is more easily transferred from the atmosphere through diffusion. In general, vertical flow SSF wetlands are less common and not as well documented as horizontal flow systems.

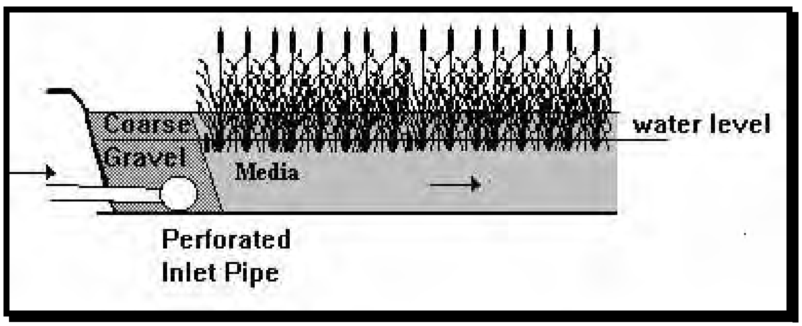

Figure 3
Profile of Typical Sub-Surface Horizontal Flow Constructed Wetland

3.0 CONSTRUCTED WETLAND TREATMENT PROCESS

Constructed wetlands consist of channels and basins in which aquatic plants, such as cattails and bulrushes are planted. Wastewater is discharged into the wetland system by either pumping or gravity. Several physical, chemical and biological processes take place in a wetland system. On average, wetlands are capable of providing removal rates ranging anywhere from 60% to over 95% for many pollutants.

There are six major biological reactions of interest in the performance of constructed wetlands: photosynthesis, respiration, fermentation, nitrification, denitrification and microbiological phosphorous removal *(Mitchell, 1996).* Chemical reactions between certain substances, especially metals, can lead to their precipitation from the water column as insoluble compounds. Exposure to light and atmospheric gases can break down organic pesticides or kill disease-producing organisms *(EPA, 1995).* Various organic compounds are lost to the atmosphere through volatilization as they enter the wetland.

The following table provides an overview of the pollutant removal mechanisms that operate in the wetland environment:

Table 1 : Overview of Pollutant Removal Processes

Pollutant	**Removal Process**
Organic Material (measured as BOD)	biological degradation, sedimentation,
Organic contaminants (e.g. pesticides)	adsorption, volatilization, photolysis, biotic/abiotic degradation.
Suspended solids	sedimentation, filtration
Nitrogen	sedimentation, nitrification/denitrification, microbial uptake, plant uptake, volatilization.
Phosphorus	sedimentation, filtration, adsorption, plant and microbial uptake
Pathogens	natural die-off, sedimentation, filtration, predatation, UV degradation, adsorption
Heavy metals	sedimentation, adsorption, plant uptake

(from : Constructed Wetlands Manual, Volume 1, Department of Land and Water Conservation, New South Wales)

3.1 Suspended Solids Removal

Most suspended solids are removed through sedimentation and filtration, as vegetation obstructs the flow and reduces velocities. In most applications, a sedimentation pond is added upstream of the wetland cells to promote the removal of larger suspended particles and minimize the chance of clogging the wetland cells. The pond can also dilute the raw influent if it is considered too strong. These processes remove a significant portion of the BOD, nutrients (mostly nitrogen and phosphorus) and pathogens.

3.2 Biochemical Oxygen Demand Removal

The remaining soluble organic material, left over after sedimentation, is aerobically degraded by bacterial biofilm that is attached to the plants. In the wetland cells the aquatic plants supply oxygen to the wetland floor through their roots, thereby promoting the aerobic digestion of organic material. Some anaerobic degradation of organic material also occurs in the bottom sediments. Wetlands provide a diversified micro-environment which plays an important role in pollutant processing. Various processes occur within the water column, on the plants, in the wetland substrate and in concentrated areas of microbial activity known as biofilms. Biofilms are formed as bacteria and microorganisms attach themselves to the plant stems, the plant roots and the substrate matrix to form a biological filter from the water surface to the wetland floor. As water passes through the thick growth of plants, it is exposed to this living biofilm, which provides a treatment process similar to that found in conventional sewage treatment plants.

3.3 Nitrogen Removal

Wetlands promote the process of nitrification/denitrification which removes nitrogen from the water. In simple terms, bacteria in the water (Nitrosomonas) oxidizes ammonia to nitrite in an aerobic reaction. The nitrite is then oxidized aerobically by another bacteria (Nitrobacter) forming nitrate. Denitrification occurs as nitrate is reduced to gaseous forms under anaerobic conditions in the litter layer of the wetland substrate. This reaction is catalyzed by the denitrifying bacteria Pseudomonas spp. and other bacteria.

Wetland plants play an important role in nitrogen removal by providing biofilm attachment points and by supplying oxygen for nitrification in the root zone *(Brix 1987).* Interestingly enough, plants generally take up only a small portion of the incoming nutrients (<5%).

3.4 Phosphorus Removal

Phosphorous removal in wetlands is based mainly on the phosphorous cycle and can involve a number of processes such as adsorption, filtration, sedimentation, complexation/precipitation and assimilation/uptake. In Ontario, the effluent from constructed wetlands will often fail to meet effluent criteria with respect to phosphorous. This is the case when the system is constructed in a location where there is no adequate receiving stream for the wetland effluent. In such cases, post wetland polishing may be required in the form of vegetated filter strips, irrigation or phosphorous adsorption media. This is discussed later in the manual.

3.5 Pathogenic Bacterial Removal

Pathogen removal in constructed wetlands is achieved through a combination of natural die-off, temperature, sunlight (ultraviolet light), water chemistry, predatation and sedimentation. Despite the presence of water, a wetland is a hostile place for pathogens. Constructed wetlands have been shown to reduce incoming pathogens numbers by up to five orders of magnitude *(Reed et al., 1995).* A proportion of pathogens are removed by sedimentation, especially those attached to particles. Biofilm filtering removes some of the pathogens by direct contact. Predatation occurs as the wetland provides a habitat for a variety of microorganisms, some of which are pathogen predators such as zooplankton. The shallow water columns found in wetlands allow the penetration of ultra-violet light from sunlight which also destroys pathogens.

Pathogens of concern in aquatic treatment systems are parasites, bacteria and viruses. Because it is impractical to monitor all pathogens, indicator organisms such as Fecal coliform (E. Coli), Fecal streptococci and coliphage MS-2 are used to measure the removal efficiency of a treatment system. These indicators are used because they are easy to monitor and correlate with populations of pathogenic organisms. Because of the natural sources of pathogens in natural treatment system (wildlife), it is unrealistic to expect complete removal without disinfection. Constructed wetlands, however, have been shown to provide pathogen removal rates in the order of 80% to 90%. One must keep in mind that a wetland with a high pathogen count in the influent will have a greater removal rate than one with a low count. Negative removal rates can be encountered if the influent count is less than the in situ production rate (due to wildlife).

Although pathogens are often a source of concern when water reclamation is considered, we must keep in mind that numerous water and sludge reclamation systems are in use in the world without any adverse effect on the general population. The American National Research Council published a paper in 1996 entitled *"Use of Reclaimed Water and Sludge in Food Crop Production"*. The paper reported that there has been no reported outbreaks of infectious diseases associated with a population's exposure, either directly or through food consumption pathways, to adequately treated and properly distributed reclaimed water or sludge applied to agricultural land. The paper also mentions that the most extensive literature on human exposure to wastewater is concerned with the infectious disease risk to wastewater treatment plant operators and maintenance personnel.

A review of the literature by the Council concluded that clinical disease associated with occupational exposure among these workers is rarely reported. It is therefore not unreasonable to assume that using treated reclaimed water on agricultural land would present an even lower risk to agricultural workers and end users of the product. The report concluded by stating that the potential added increment of pathogen exposure from the proper reuse of reclaimed water or sludge is minuscule compared to our everyday exposure to pathogens from other sources (i.e. such as person to person contact and prepared foods).

3.6 Toxin Removal

Wetlands have an excellent buffering capacity for toxins as well as the ability to dilute and break down various toxins (to a degree). These processes, however, form part of the complicated science of ecotoxicology and would require a manual in itself to further explain them. We do know, however, that hydrocarbon materials are known to degrade in constructed wetlands with good removal efficiencies reported for phenol, benzene, toluene and crude oils *(White et al., 1996)* .

4.0 CONSTRUCTED WETLAND DESIGN

Before any wastewater treatment design process can begin, the wastewater to be treated must be evaluated. The following sections discuss wastewater evaluation and two methods of wetland sizing: pollutant loading rates and first order reaction kinetics.

4.1 Types of Wastewater

Surface flow constructed wetlands in rural settings have been used to treat a variety of wastewaters ranging from weaker municipal wastewater to more concentrated manure runoff. Alfred College of the University of Guelph has been involved in the construction and monitoring of two constructed wetlands for the treatment of dairy farm waste (i.e. manure pile/ feedlot runoff and milkhouse waste). The studies have shown that average influent concentrations for manure pile runoff are approximately 1000 mg/L, 600 mg/L and 75 mg/L for BOD_5, TKN and TP respectively (see case study in Appendix A of this manual). Other rural wastes that could be treated with constructed wetlands include municipal waste from small communities, food processing waste, swine manure runoff, septage and holding tank waste, etc. Although wetlands are a proven technology, additional research (in the form of pilot studies) is still required on strong wastes such as swine manure and septage wastewater. For example, the average hog can produce BOD_5 loadings in the range of 0.32 Kg/hog/day and TKN loadings of 0.038 Kg/hog/day. Septage waste is also a very strong waste with BOD_5 concentrations in the order of 7,000 mg/L, TKN of 700 mg/L and TSS of 15,000 mg/L. Although wetland plants are capable of withstanding BOD levels up to 400 mg/L, if the influent concentration exceeds this level pretreatment must be conducted. Appendices D and E provide more detail on the treatment of such wastes in the form of theoretical design case studies.

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Wastewaters from food processing facilities are usually high in BOD/COD and suspended solids due to a high concentrations of fats, oils and grease. Some egg processing facilities can have COD's as high as 40,000 mg/L *(South West Wetlands Group, 1997)*. For such wastewaters a primary treatment system such as a reed bed is often used upstream of the constructed wetland. The American Sugar company in the United States presently uses constructed wetlands for the treatment of the wastewater produced at two of their sugar beet refineries in North Dakota. The average influent concentrations for the various pollutants, BOD of 120 mg/L, ammonia - nitrogen 35 mg/L and total phosphorus 1.25 mg/L. These influents are within acceptable ranges and primary treatment is not required. Appendix F provides more information on the use of natural systems for the treatment of food processing wastewater.

4.2 Wastewater Evaluation

Wastewater is evaluated on the basis of concentration and flowrate. Influent BOD_5, TKN, Suspended Solids and Total Phosphorus concentrations should be known prior to beginning the design process. Other parameters that could have an effect on the system include metals, phenols, oil, grease and fat. If these parameters are found in high concentrations, additional treatment may be required.

One of the most critical aspects of constructed wetland design is the proper estimation of wastewater volumes. Wastewater volume averages (daily/weekly/monthly) must be determined for all wastewater sources during different periods of the year. Wet weather periods may provide the greatest volume of water, however the pollutant concentration may be significantly less than during dry summer months (dilution factor). If an increase in hydraulic loading does not create a corresponding increase in the daily mass loading, the increase in flow can be ignored. The important factor in designing a constructed wetland is to determine the maximum mass loading expected, regardless of whether high volumes with low concentrations or low volumes with high concentrations produce the maximum load, and design for the maximum mass loading over an extended period.

Since the guidelines presented herein are for simple free surface types wetlands, similar to those found in nature, it is assumed that treatment will be limited to summer months when it is most efficient. For this reason winter storage (180 to 225 days) will most likely be required (unless the waste production is seasonal). Storage has the advantage of providing a more uniform waste concentration to the wetland and may make the design of the wetland cells somewhat easier. Section 5.2 discusses this aspect further.

Water quality parameters that need to be sampled and analyzed in most situations consists of BOD_5, TSS, bacteria, Nitrogen and Phosphorous. These are pollutants that originate from organic sources that will be of most interest in treatment. In some cases other parameters such as metals and phenols may also require treatment, however these parameters are for specific applications as opposed to general organic waste.

Wastewater volumes are also important in determining the water budget for the constructed wetland. More information on this topic is presented in Section 6.3.

4.3 Pollutant Loading Rate Method

The design of a constructed wetland is dependent upon the volume and concentration of the incoming wastewater. Accurate determination of the various pollutants is critical in determining the size and type of constructed wetland.

Constructed wetlands can be designed on the basis of mass loading of a specific pollutant on a daily loading basis. Designers must have accurate information on the flow volume of and the pollutant of the wastewater. Daily flows in cubic meters (m^3) times the concentration of a specific pollutant (mg/L) provides an estimate of the mass of pollutant (kg/day) requiring treatment that can then be used to estimate the effective treatment area required with the recommended loading rates (i.e. kg/ha per day for BOD_5, TSS, NH_3 or some other parameter) (Hammer, 1994).

For example (Hammer, 1994):

Average wastewater flow rate = 3,000 m^3/day
BOD_5 = 150 mg/L

Daily mass loading = (3,000 m^3/day * 150 mg/L) / 1,000
= 450 kg/day

Based on a BOD_5 loading rate of 100 kg/ha/day, the required effective treatment area becomes: 450/100 = 4.5 ha.

Loading rates should be calculated for TKN and TP. Allowable daily loading rates are 3 kg/ha/day and 0.2 kg/ha/day for TKN and TP, respectively.

NOTE:

A 1996 review of the North American Treatment System Database (NADB) by *Kadlec and Knight* found that the 3 kg/ha/day TKN guideline may be somewhat conservative. A figure of approximately 7.6 kg/ha/day was the average in the database. It is therefore recommended that the designer use a figure in the range of 3-7 kg/ha/day, with the lesser figure being more conservative.

4.4 First Order Kinetic Rate Equations Method

Constructed wetlands are typically modeled as a plug flow reactor using first-order reaction kinetics to describe the system.

$$C / C_i = \exp(-k_v t) \qquad [1]$$

Where: C_i = initial pollutant concentration, mg/L
C = pollutant concentration at time t, mg/L
k_v = volumetric reaction rate constant, d^{-1}
τ = hydraulic residence time, d

τ is defined by equation .

$$t = {eAh}/{Q} \qquad [2]$$

Where: A = wetland surface area, m^2
e = porosity of the wetland (~95% for surface flow wetland),
h = average water depth, m
Q = flowrate through the wetland, m^3/day

To account for temperature effects, the rate constant k_v is adjusted using the Arhennius equation:

$$k_{v,T} = k_{20}q^{(T-20)} \qquad [3]$$

Where: q = is the Arhennius coefficient,
T = is the temperature, °C
k_{20} = is the value at 20°C

Kadlec and Knight *(1996)* use a residence time distribution (RTD) to describe the nominal detention time within the wetland. The RTD is the probability density function for residence times in the wetland. The time function is defined by *(Kadlec and Knight, 1996):*

f(t)Δt = fraction of incoming water which stays in the wetland for a length of time between t and t + Δt [4]

where f = RTD function, d^{-1}
t = time, day.

Kadlec and Knight *(1996)* recommend using a tracer test to determine the RTD function for a given wetland. An impulse of dissolved inert tracer material is injected into the wetland inlet and then the tracer concentration as a function of time is measured at the wetland outlet.

For some pollutants background levels are incorporated into the plugflow kinetic equation. For example, the background level for BOD in a constructed wetland is greater than zero. Biological activities in the wetland can cause the background level to vary from 2 to 30 mg/L *(Higgins et al., 1999)*. This only has an effect if the inlet BOD concentration is lower and/or if the target outlet concentration were set at 20 or 25 mg/L *(Higgins et al., 1999)*. Equation 1 is modified to allow for background levels of contaminants:

$$\frac{(C - C^*)}{(C_i - C^*)} = \exp(-k_v t) \qquad [5]$$

Where: C_i = is the influent pollutant concentration, mg/L
C^* = is the background pollutant level, mg/L

The background level method is only used for certain pollutants (e.g., for BOD, suspended solids, organic nitrogen) but is not used for pollutants were the expected to be zero (e.g., for ammonia nitrogen).

Rate constants and the values of C* are site specific and can be measured during a treatability test. These values have also been published in the literature for actual wetland situations.

Table 2: Temperature Coefficient and Rate Constants *(Reed et al., 1995)*

Parameter	BOD removal	NH_4 removal	NO_3 removal
C*	6	0.2	0.2
k_v, 20°C (d^{-1})	0.678	0.2187	1.000
θ	1.06	1.048	1.15

Kadlec and Knight *(1996)* recommend different values for the kinetic rate constants and temperature coefficients. These are listed in Table 3.

Table 3: Kinetic Rate Constants and Temperature coefficients

Parameter	BOD	Org N	NH_4	NO_x	TN	TP
k20, m/yr	34	17	18	35	22	12
θ	1.00	1.00	1.05	1.04	1.09	1.05
C*, mg/L	$3.5+0.053C_i$	1.5	0.00	0.00	1.50	0.02

Kadlec and Knight use areal rate constants, which can be related to the volumetric rate constant, k_v, by the following equation.

$$k = k_v he \qquad [6]$$

Where: k = is the areal rate constant, m/yr
h = is the wetland depth, m

NOTE:

Although the Kinetic loading rate method is a more complex and accurate method, the author's experience with the pollutant loading rate approach has yielded good results with high removal rates. For small simple rural systems such as those found on agricultural lands, the pollutant loading rate method will provide a simpler method of sizing the system while still yielding high removal rates.   **Since this manual is directed at those seeking a simple low cost solution, the pollutant loading rate method is used from this point on.   If a larger and more complex system is considered, the Kinetic Loading rate method may be more appropriate.**

5.0 SYSTEM COMPONENTS

5.1 General

The main design objectives for a wastewater treatment constructed wetland is to provide a system that:

- is capable of providing a high level of treatment and discharging a relatively clean water;
- is inexpensive to build;
- is inexpensive and simple to operate; and
- is self-maintaining.

Although we have discussed various types of constructed wetlands in Section 2.0, the most widely used system in North America is the free surface (Emergent macrophyte) type system. This type of system is relatively simple, easy to construct and operate and economical. Variations of this type of system have been developed such as adding aeration, artificial media or a greenhouse type cover. These variations, however, only add to the complexity and cost of the system, thereby compromising the objectives outlined above. Other natural modifications however, such as combining emergent macrophytes with submergent and free floating species, may be inexpensive and beneficial to the system.

Usually when one is considering a constructed wetlands as a means of wastewater treatment, one is looking for a simple and inexpensive type of system. For this reason the following design considerations are for a free surface type system, similar to a natural wetland.

5.2 Storage Lagoon

Since a free surface wetland system is most efficient during warmer periods, it is best that the wetland cells only operate during the growing season. For this reason, winter storage is required. The most practical method of storage is to construct an earthen lagoon, with an impervious liner, large enough to hold approximately 6 months (180 to 225 days) of waste volume (depending on the geographic location). If the storage area is not covered, precipitation volumes need to be considered. Section 6.3 provides further information on hydrologic considerations.

The storage lagoon has the added benefit of providing some pre-treatment and load balancing. This is especially practical if the incoming waste is excessively strong, such as livestock waste (high BOD_5) or septic tank waste (high total suspended solids). As the residence time is long and regular, the removal of suspended solids can be quite high. In Alabama, a lagoon used to treat calf manure and washwater, reduced the concentrations of TKN, TSS and BOD by 55%, 98% and 94%, respectively (*Payne, 1983*). TKN is removed by sedimentation of solids (including biomass) and volatilization of nitrogenous gases such as ammonia (there is little conversion into nitrate because of the lack of oxygen). According to *Cooper et al. (1996*), loadings of .04 kg BOD_5/m^3/day with detention times of 50 days can achieve a 50% reduction in BOD_5 for climates of western Europe.

Depending on the type of application, the following conservative removal rates are anticipated from an anaerobic storage lagoon with approximately 6 months of storage:

- BOD_5: 50-60%
- TKN: 20-30%
- TP: 30-40%
- TSS: 90-95%

Anaerobic lagoons used for storage of organic waste will need dredging of the substrate approximately every 5 to 10 years. If the organic waste has already been reduced (such is the case with septic tank waste), the substrate sludge will accumulate at a much greater rate. The sludge will have a solids concentration of approximately 5% and will require removal every two years. The removal can be achieved with a sludge pump, where the effluent is discharged directly onto fields and plowed into the soil. This will give the user the flexibility of choosing the right time for disposing of the sludge and allowing the disposal/plowing operation to proceed in one step. Another removal method is to allow the lagoon to dry and remove the waste with a mechanical shovel or front end loader. More information is provided on this topic in section 6.10.3

5.3 Pre-Treatment (Facultative Pond)

Facultative ponds are ponds with a depth between 0.7-1.8 meters. Due to their depths, these ponds combine aerobic and anaerobic processes to provide efficient treatment. BOD_5 concentrations can be reduced by as much as 70-85% under good conditions (warm temperature). This system can reduce pathogen concentrations by up to 99%. The usual detention time is 5 to 30 days. Anaerobic fermentation occurs in the lower layer and aerobic stabilization occurs in the upper layer.

In the United States, the recommended loading rate for climates in which temperature is higher than 15^0C is 100 kg/ha/day (*Reed et al., 1988*). Such a loading should produce an effluent with a BOD_5 lower than 30 mg/L. In Ontario, *Weil et al. (1997*) found that a facultative pond designed with a loading of 150 kg/ha/d produced an effluent with an average concentration of 216 mg/L BOD_5. Even though the concentration is not in the range encountered in the warmer climate of the United States, this value is lower than the 400 mg/l of BOD_5 necessary to enter the constructed wetland. Facultative ponds can also reduce TKN by approximately 90% (*Weil et al., 1997*).

Depending on the type of application, the following conservative removal rates are anticipated from a facultative pond with a loading of 100 - 150 kg/ha per day:

- BOD_5: 50-60%
- TKN: 20-30%

As with the storage lagoon, precipitation needs to be considered when sizing the facility (See section 6.3).

5.4 Wetland Cells

Some of the most successful wetland designs include a combination of free water surface wetland (FWS)#1 followed by a pond wetland and then by a free water surface wetland (FWS#2) sequentially located in the system. *Hammer (1997)* described this sequence of treatment in the following manner (See figure 4.0):

5.4.1 Free Water Surface (FWS) Wetland Cell

The first and third cells are shallow basins with densely growing marsh vegetation - typically cattail (Typha), bulrush (Scirpus validus or cyperinus), reed (Phragmites) or rushes (Juncus, Eleocharis), in 10 to 20 cm of water. The function of the first FWS wetland is for the removal of BOD_5, suspended solids (TSS), metals, pathogens and complex organic as well as ammonification. The initial operating water depth is approximately 8 to 10 cm above the soil surface, gradually increasing to 15-20 cm over the next 15 to 20 years as peat accumulates in the FWS wetland.

The second FWS wetland is physically and operationally the same as the first and promotes denitrification as well as the removal of BOD_5, suspended solids, metals, pathogens and complex organics.

5.4.2 Pond Wetland

The second compartment is a constructed pond wetland with 0.75 to 1.5 m water depths. Duckweed (Lemna) can grow on the surface of the pond as well as various algae within the water column. Submerged pondweeds with linear, filiform leaves (Potamogeton, Ceratophyllum, Elodea, Vallisneria) are planted in shallow portions of the pond to increase the surface area for microbial attachment. The pond wetland provides further reduction of BOD_5, nitrification and phosphorous removal. Furthermore, an intermediate pond wetland within the FWS wetland cells will help prevent short-circuiting by allowing the re-distribution of flow. Operating depth is typically 0.9 to 1.3m throughout the years of operation.

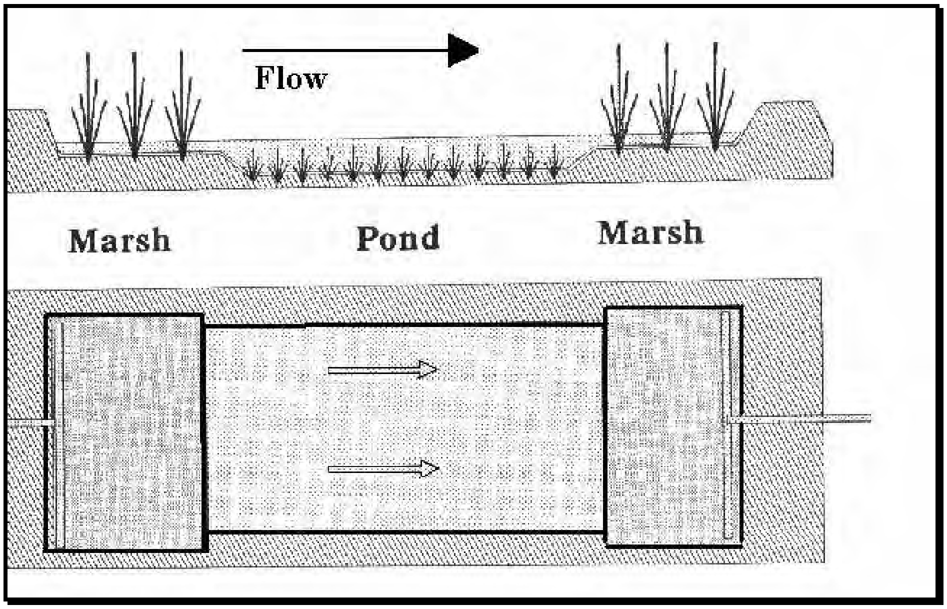

Figure 4 - Typical FWS wetland - pond wetland - FWS wetland layout (Hammer,1997)

As with facultative ponds, the design of FWS wetland cells is based on mass loading rather than hydraulic loading. Recommendations with respect to the required loading rate depends on the type of effluent that is required. A lower quality effluent (secondary discharge standard) may only be necessary if post wetland polishing is used such as spray irrigation of grass filter strips. The estimated expected effluent quality would be as follows*: (Hammer 1994)*:

- BOD_5 & TSS < 30mg/L,
- Fecal coliform < 200 CFU/100 ml,
- pH 6-9,
- Dissolved oxygen > 4mg/L

For this level of effluent quality, the following loading rates are recommended: (*Hammer 1994)*

- BOD_5 and TSS: <100 kg/ha per day
- Hydraulic Loading: <1000 m^3/ha per day
- Retention time: > 5 days

If advanced effluent quality is required, such as the following *(Hammer 1994):*

- BOD_5 & TSS < 20mg/L,
- Fecal coliform < 100 CFU/100 ml,
- pH 6-9,
- Dissolved oxygen > 4mg/L,

- PO_4 < 1 mg/L,
- NH_3 < 4mg/L

The following loading rates are recommended *(Hammer 1994):*

- BOD_5 and TSS: <70kg/ha per day
- TKN or NH_3: <3 kg/ha per day
- TP: <0.2 kg/ha per day
- Hydraulic Loading: <500 m^3/ha per day
- Retention time: > 10 days

NOTE:

The design area is based on the total wetland area (FWS#1 + pond + FWS#2) and is calculated from the toe of the inside berm and not the crown of the berm. Marsh cells should have a length to width ratio of 3-5:1 while ponds can be as low as 1:1.

5.5 Post Wetland Polishing

In Ontario, obtaining approval from the Ministry of the Environment for the discharge of constructed wetland effluent to a receiving body of water or a dry ditch may be difficult. It is important that the designer contact the Ministry prior to design to discuss guideline requirements with respect to the discharge. One of the feficieencies with summer discharge to a low flow receiving stream is the phosphorous concentration in the effluent. For this reason, post wetland polishing may be required. The alternatives presented in this section consist of using vegetated filter strips as a filtering medium or using the wetland effluent for irrigation purposes. New research currently underway in the field of phosphorous removal is also discussed in this section.

5.5.1 Vegetated Filter Strips

The use of vegetated filter strips (VFS) have long been recognized as an important control measure in reducing surface runoff and removing some of its constituents. They are now used for various purposes including purification of municipal, agricultural and food-processing wastewater; protection of watercourses from logging, construction, strip mining, agricultural practices; and water quality control facility for urban storm runoff. Vegetated filter strips are frequently referred to as buffer strips or zones, grass strips, riparian planting, overland flow system and combinations thereof.

Filter strips improve runoff quality mainly by changing flow hydraulics. The water flowing onto vegetated strips encounters more resistance, which results in lower flow velocities and thus less erosive power. This allows for more timely interaction between water and the vegetated / soil media. For effective pollutant removal, flow through filter strips must be unsubmerged (shallow), slow and uniform (*Dillaha et al., 1988*).

The two main removal mechanisms at work in vegetated filter strips used for wastewater are infiltration and deposition. Deposition of suspended particles and colloidal organic materials in wastewater is greatly enhanced in vegetated filter strips because the lower flow velocities and flow rates decrease the sediment transport capacity. Deposition is mainly governed by suspended particle size, flow rate, and filter strip dimensions and slope. Enhanced infiltration permits the entry into the soil profile of fine suspended particles or soluble pollutants that are found in runoff. Once in the soil media, physical, chemical and biological processes can decompose and transform some pollutants to make them available to plants. Other mechanisms such as adsorption to plant and soil surfaces and absorption of soluble pollutants by plants are at work. Vegetation provides nutrient uptake and a medium for biological growth. Nutrients are taken away when the vegetation is harvested.

When purifying wastewater, inflow to the vegetated filter strips is generally continuous. In such systems, the inflow comes from a storage facility (in our case it is from the wetland treatment system) at a given application rate and for a given application period. The application period can vary from a few days to a month and is generally alternated with rest periods to allow for filter maintenance. Since the subsoil remains in a quasi-saturated state, biological growth develops within the grass-soil media. The extent of this biological growth has been directly linked to the removal of BOD_5 and phosphorous in previous studies *(Overman and Wolfe. 1986, Payer et al. 1987)*

The vegetative filter strips proposed in this manual would be used for polishing wetland effluent prior to discharge to a watercourse. ***For this reason the wetland system upstream of the filter strip must be designed for the highest effluent quality.*** Although not much information is available on phosphorous removal using filter strips, it is believed that the sizing equation presented herein can significantly reduce phosphorus concentrations for low flow systems. The Dignard constructed wetland case study presented in Appendix A shows that phosphorous concentrations in the effluent from the wetland system, which is in the order of 5.0 mg/L, is reduced to near background levels of 0.05 mg/L after the filter strip. One must keep in mind, however, that the size of the Dignard filter strip can accommodate the system influent flow of 11 m^3/day, when in fact evapotranspiration effects reduces the outflow to approximately $1/10^{th}$ of the inflow.

Previous studies by *Chaubey et al. (1994)* identified removal rates in the order of 67% to 92% for total phosphorus using filters of 3 to 21 meters in length. Total Kjeldahl Nitrogen removal was similarly high and varied from 65% to 89% for filters of 3 to 9 meters in length. Work performed in Ontario by *Michael Toombs (1997)* recommended filter strip lengths of 90 m to 260 m for beef feedlot runoff. *Metcalf and Eddy (1991)* give as a general guideline for overland flow systems lengths of 30 m to 45 m. For the quality of effluent that is expected from a constructed wetland , ***filter strip lengths should range between 45 m and 90 m.***

The application rate is the most important design parameter for an overland flow system. *Metcalf and Eddy (1991)* recommend rates ranging from 0.25 to 0.60 m^3/m length per hour (m^3/m.h). *Overman and Wolfe (1986)* have suggested using a lower application rate of 0.1 m^3/m.h to keep ammonium nitrogen concentration below 2.0 mg/L. Since we are aiming for a direct discharge into a watercourse, ***a strict application rate of 0.05 m^3/m.h is recommended to promote adequate phosphorous removal.***

The wetland effluent can be applied to the filter strip over a 24 hour period, however a rest period is required to permit the soil to dry before harvesting. It is recommended that application be continuous for a 2 week period followed by a 2 week rest period. If a single filter strip system is used, the upstream wetland cells have to be designed to account for storage during the 2 week rest period and the filter strip has to take into consideration the increased loading rate due to the wetland storage. An easier alternative would be to design two filter strips operating for 2 week periods on an alternating basis.

Since the flow entering the filter strip system has been previously treated by a facultative pond and wetland cells, pathogen concentrations entering the filter strip system should already be low. Even if local wildlife activity causes an increase in the wetland's coliform count, the filter strip should be effective at reducing these counts to acceptable levels (<100 counts/100 ml). Although there is not much documentation on pathogen removal in filter strips, work done by *Young, Huntroids and Anderson in 1980* successfully reduced the total coliform count from a 14 m deep beef feedlot to 1000 counts/100 ml using a 35 m long filter strip (beef feedlots can have total coliform counts much greater than 100,000 counts/100 ml). Given the quality of the effluent from the wetland system, further polishing from the filter strip should provide a total removal rate from the overall system (wetland + filter strip) of 90% or greater.

A note of caution is required. Studies by Barrington found that some pathogenic microorganisms found in manure can survive in soil for lengthy periods of time. Salmonella bacteria can live in the soil for 7 to 168 days, Erysipilothrix bacteria for 21 days, Enterovirus for 25 days to 170 days, Polivirus for 32 days and the Ascaris Lumbricoidesova for up to 2000 days *(Barrington 1991)*. These pathogens could therefore be released subsequently in flowing runoff over the filter strips. Most of the studies done on this topic, however, have been for filter strips used as a **primary treatment system.** By using the filter strip as a polishing system, these concerns are reduced significantly.

There are currently no uniform design criteria, and no universally accepted design methods for the sizing of vegetated filter strips. Based on information presented in this manual, we therefore recommend the following equation to determine the total area for a vegetated filter strip:

$$\textbf{Area (m}^2\textbf{)} = \textbf{(Q x L) / (R x C)} \qquad [7]$$

Where: Q = effluent flow rate (m^3/h)

L = Length of filter strip (recommended 45 m to 90 m)
R = Application rate (recommended at 0.05 m^3/m.h)
C = Ratio of total period / rest period (recommended at 0.5)

For example, if we assume that the effluent volume from a constructed wetland is approximately 100 m^3/day, and that a filter strip operating 12 hours a day is required, the area would be:

$Q = 100/12 = 8.3\ m^3/hour$
$L = 90\ m$ (assumed)
$R = 0.05\ m^3/m.h$ (recommended)
$C = 0.5$ (recommended)

$A = (8.3 * 90)/ (0.05 * 0.5) = 29,880\ m^2 = 3\ ha$ (two strips of 1.5 ha each)

For a system with a low effluent volumes, filter strips can be cost effective if pumping is not required. With increased effluent volumes, filter strips may be less effective and less economical as large parcels of land are required. In such cases, land irrigation should be looked into.

5.5.2 Irrigation

A second alternative for the polishing of wetland effluent is to use the effluent for irrigation purposes. By irrigating the effluent it is possible to dispose of both nutrients and excess water (by allowing little or no runoff). The goal is to bring to the plants only the amount of water they require to prevent any percolation. Thus the water needs = real evapotranspiration - effective precipitation - storage of water in soil.

Since the wetland effluent is being irrigated on vegetation, nutrient levels in the effluent do not need to be as strict as for direct discharge into a watercourse. For this reason the wetland system can be smaller in size. The designer will need to evaluate the most economical sizes for both wetlands and irrigation fields.

To reduce the required irrigation area, it is important to use plants that require a significant amount of water. One alternative to grass crops is to use deciduous trees, such as the European Willow and the hybrid Poplar, which have a water consumption rate of 1.5 to 2.0 times that of grasses.

The required irrigation area should be sized based on both nutrient and water requirements. As a rule of thumb the requirements for nitrogen and phosphorous are roughly the same for trees and grass forage. The required area can be sized based on a total nitrogen requirement of 140 Kg/ha per year to 350 Kg/ha/year, and a total phosphorous requirement of approximately 40 Kg/ha per year. For example, if the wetland effluent has a concentration of 200 mg/L of total nitrogen and that approximately 1000 m^3 is discharged to the irrigation lands during the growing season, the total nitrogen loading to the irrigated area would be 200 kg. Based on a crop requirement of 250 Kg/ha (midpoint of range), the size of the irrigated area would need to be 0.80 ha.

Note:

In Ontario, the Ministry of the Environment does not permit a percolate nitrogen concentration greater than 10 mg/L NO_3 as N. The designer should remember this if an infiltration type system is being considered.

The requirement for phosphorous is somewhat more complicated since the level of phosphorous that already exists in the soil may have to be accounted for prior to loading additional phosphorous onto the land. If the soil has a high level of phosphorous, the application rate must be lowered accordingly so that the total phosphorous does not exceed 40 Kg/ha per year. Assuming that the existing Phosphorous in the soil is not a concern, and that the wetland effluent from our previous example has a concentration of 5 mg/L of total phosphorous, the total loading to the irrigated area is 1,000 m^3 x 5 mg/L x 10^{-3} = 5 Kg. Based on the crop requirement of 40 Kg/ha, the size of the irrigated area would need to be 5 kg 40 Kg/ha = 0.13 ha. The nitrogen requirement of 0.8 ha (computed previously) therefore governs.

The water requirement for crops is dependent on various factors such as the type of crop, the type of soil, the climatic region etc. In Ontario, the Ministry of the Environment (MOE) has guidelines for the land application of treated sewage effluent. Although these guidelines have been written for the land application of treated municipal sewage effluent, many aspect of the guidelines may still apply to rural waste. As mentioned in the introduction to section 5.5, it is important that Ontario designers contact the MOE to discuss guidelines requirements. This manual discusses the MOE guidelines with respect to the effluent application rate since it is critical is sizing the required irrigation area.

Assuming that minimum infiltration and runoff is the objective (i.e. maximum evapotranspiration), the amount of sewage effluent applied over a season is based on the crop water deficit. The MOE defines the crop water deficit as being the sum of the potential evapotranspiration and the soil moisture holding capacity minus the May to September precipitation. The irrigation season can be determined using the frost free period for the area (see Table 4), however, the MOE does not allow for an irrigation season in excess of 100 days for the purpose of design. The effluent application amount for ***perennial grasses*** can therefore be determined using the following method

- Divide the irrigation period by the number of rest days (Table 5.0) to obtain the number of days the land will be irrigated.

- Multiply the number of days by the application amount (Table 5.0) to obtain the total amount of moisture needed by the grass.

- Subtract the mean May to September precipitation (Table 4.0) to obtain the seasonal effluent application amount.

- Use the lowest recommended application rate (cm/h) to determine the flow rate.

Table 4.0 - Climatic Summary For Ontario

Location	Mean Annual Frost-Free Period		Mean Annual Growing Season		Mean Grow Season Precipitation (cm)	Mean Annual Potential Evapotranspiration (cm)
	Dates	Days	Dates	Days		
Leamington	May 01-Oct 20	172	Apr 05-Nov 12	221	36	66
Niagara Fruit Belt	May 05-Oct 15	163	Apr 10-Nov 10	215	36	64
Kent and Essex	May 05-Oct 15	163	Apr 08-Nov 11	218	36	66
Lake Erie Counties	May 12-Oct 10	151	Apr 10-Nov 08	213	36-38	64
Lake Ontario Shores	May 12-Oct 08	149	Apr 12-Nov 03	206	36	61
Prince Edward County	May 12-Oct 10	151	Apr 12-Nov 05	208	36	61
Lake Huron, Georgian Bay	May 15-Oct 10	148	Apr 15-Nov 05	205	38	61
South Slopes	May 15-Oct 05	143	Apr 13-Nov 03	205	38	61
Huron Slopes	May 20-Sep 30	133	Apr 17-Oct 31	198	38-41	58
Simcoe and Kawartha	May 18-Sep 28	133	Apr 18-Oct 28	194	36-38	58
Eastern Counties	May 15-Sep 28	136	Apr 15-Oct 28	197	38	61
Manitoulin	May 25-Sep 28	126	Apr 23-Oct 28	189	33-36	56
Muskoka	May 25-Sep 25	123	Apr 22-Oct 27	189	38-41	58
Renfrew	May 18-Sep 25	130	Apr 18-Oct 27	193	36-38	58
Dundalk Upland	May 31-Sep 20	113	Apr 20-Oct 25	189	41	56
Haliburton Slopes	May 25-Sep 17	115	Apr 22-Oct 24	186	36-38	56
Algonquin Park	May 31-Sep 20	113	Apr 25-Oct 21	180	38	53
Sudbury	May 21-Sep 20	112	Apr 25-Oct 24	183	36	56
Thunder Bay	May 31-Sep 12	104	Apr 26-Oct 17	175	41	53
Timiskiming	Jun 10-Sep 13	96	Apr 27-Oct 15	172	41	53
Superior	Jun 05-Sep 15	103	May 06-Oct 15	163	41	51
Northern Clay Belt	Jun 08-Sep 07	92	May 07-Oct 13	160	38-41	51
English River	May 30-Sep 15	108	May 03-Oct 13	164	36-41	53
Height of Land	Jun 15-Sep 02	80	May 05-Oct 13	162	41	48
Albany	Jun 12-Sep 05	86	May 15-Oct 08	154	38	46
Patricia	Jun 18-Aug 31	75	May 24-Oct 01	131	36	41

(Modified Table 21.1 from Chapter 21 of MOE guidelines on the design of Water and Sewage Treatment Plants)

Table 5.0 - Moisture Requirements For Perennial Grasses

Soil	Application Amount (cm)	Period Between Irrigation Applications (days)	Recommended Application Rate (cm/h)
Well Drained Soil	3.3	5	0.6-1.9
Loamy Sand	4.3	6	0.6-1.3
Light colored Loams and Sandy Loams and good drainage	5.1	7	0.6-1.3
Dark Colored Loams and Sandy Loams with fair to poor drainage	6.9	10	0.6-1.3
Clay Loams	6.1	9	0.4-1.0

(Table 21.2 from Chapter 21 of MOE guidelines on the design of Water Treatment Plants and Sewage Treatment Plants)

If we take our previous example of 1000 m^3 of wetland effluent, and assume a clay soil in Eastern Ontario, the following irrigation area would be required:

- Irrigation period = 100 days (max. design period as per MOE)
- Number of irrigation days = 100 (period) / 9 (rest period from Table 5.0) = 11 days
- Moisture requirement of perennial grass = 6.1 cm/day (Table 5.0) x 11 days = 67.1 cm
- Effluent irrigation = 67 cm (moisture requirement) - 38 cm (May to Sept. precipitation from Table 4.0) = 29 cm
- Required area = 1000 m^3 / 0.29 m = 0.34 ha.

The land area based on Nitrogen requirement (0.8 ha) still governs.

NOTE:

The above method is a simplified approach from the MOE guidelines for the application treated sewage effluent. There may be more complex methods with varying results. The designer must choose a method that fits his/her geographical location, and the type of crop being considered.

General Observation on Existing Irrigation Practices:

The Ministry of the Environment guidelines also stipulate that the treated effluent cannot be irrigated on crops used for direct human consumption. For crops used for animal consumption, the effluent should have a mean bacteriological count of 100cnts /100 ml for fecal coliform and 1000cnts/100 ml total coliform. It is unlikely, however, that disinfection would be required for systems discussed herein since constructed wetlands should be able to reduce the bacteriological count by upwards of 90%. One must keep in mind that the irrigation water that would be provided by such systems would often be of better quality than that of local water courses. For example, sampling of watercourses within agricultural areas in the South Nation River watershed in eastern Ontario has yielded the following results:

South Nation River at Plantagenet:

E.coli avg.	= 125 cnts/100 ml (max 4500)
Fecal coliform avg.	= 23 cnts/100 ml (3800 max)
Total coliform avg.	= 37000 cnts/100 ml

Scotch River:

E.coli avg.	= 916 cnts/100 ml (max 4200)
Fecal coliform avg.	= 314 cnts/100 ml (max 15000)
Total coliform avg.	= 1,000,000 cnts/100 ml

Bear Brook:

Fecal coliform avg.	= 168 cnts/100 ml
Total coliform avg.	= 33000 cnts/100 ml
Fecal Strep avg.	= 205 cnts/100 ml

(Source: South Nation Conservation)

The above results indicate that in many instances, irrigation water from a constructed wetlands can be better than water from a rural watercourse.

Should the use of constructed wetland water for irrigation purposes become a concern, consideration should be given to using trees as the irrigation crop. The use of trees as the irrigation crop allows the designer to make use of the higher moisture demand for trees (approximately 1.5 to 2.0 times greater than that of grass), the longer irrigation season and the deeper root system to minimize the irrigation area. Such systems are not only effective in reducing the irrigation area, but they have much less maintenance since the crop is harvested only once every 6 to 12 years. Furthermore, since the crop is not harvested often or for consumption, the concerns regarding pathogens are virtually nil.

The most common type of trees used for irrigation are the European Willow and the Hybrid Poplar. The European Willow is a moisture loving plant that is very resistant. The tree has sprouts during 15 to 20 years, which makes it easy to replant new trees to ensure long term success. The Hybrid Poplar is also popular due to its large water needs and fast growth. Hybrid Poplars, however, seem to have problems growing in heavy clay soils. The use of poplar trees for irrigation has been studied and applied by CH2M Hill in the United States (CH2M Gore&Storie in Ontario). The company has also derived an efficient irrigation process based on micro-spray technology.

The approach used to size the irrigation area for trees is based on a water budget approach. The following steps should therefore be followed:

1. Determine the effective precipitation for the area (assume 75% is effective, the remaining 25% is lost by interception, percolation and runoff). Monthly precipitation data should be used.

2. Determine the real evapotranspiration for the crop used on a monthly basis (assume 750 mm to 1000 mm per year for the European Willow).

3. Compute the initial holding capacity of water in the soil assuming that the trees will use the first 0.8 to 1.0 m of soil (even thought the roots are much deeper). For example, clay soils can have a holding capacity of approximately 10 mm per 10 cm of soil.

4. Prepare a Water Balance Table for the irrigation period on a monthly basis. The water need for the trees is estimated as being the real evapotranspiration - effective precipitation - soil holding capacity.

If we take our previous example for grass crops, the water balance table would look like Table 6 below (assuming a real evapotranspiration of 850 mm for the European Willow and a soil depth of 80 cm - clay type soil):

Table 6.0 - Water Balance for European Willow - Eastern Ontario

Month	Real Evapotra. (mm)	Precip. (mm)	Effective Precip. (mm)	Holding Cap. of Soil (mm)	Water Need (mm)
January	0	55	41	n/a	0
February	0	55	41	n/a	0
March	0	59	44	n/a	0
April	0	65	49	n/a	0
May	121	68	51	50	20
June	184	80	60	30	94
July	218	85	64	0	154
August	174	85	64	0	110
September	107	80	60	0	47
October	46	68	51	0	0
November	0	74	56	0	0
December	0	73	55	0	0
Total	850	847	636	80	425

In the above table, we can see that irrigation would be required from May to September. The sum of the Monthly real evapotranspiration - Effective Precipitation - Initial water Holding capacity of the soil = 425 mm. This is what the trees require to grow optimally. The effluent volume (from our previous examples) is 1000 m^3 per year, therefore the land requirement is 1000 m^3 / 0.425 m = 2353 m^2 = 0.24 ha. This value is approximately 30% less than that for the grass crop, however, again it is the nitrogen requirement that governs (0.8 ha). If the wetland, however, is sized to minimize the Nitrogen effluent concentration, the irrigation area would be substantially reduced.

From the monthly water balance table, a delivery system can be sized. The system should be sized to deliver irrigation water during the greatest demand month (July in our case). The designer would need to determine the maximum flow the delivery system will require in order to size the pumps and pipe diameter. Various types of irrigation systems can be used such as gravity sloped beds, in which a perforated pipe is installed at the crown of a sloped field, drip irrigation and spray irrigation, which are widely used on agricultural land and micro-spray systems which are used for tree plantations (CH2M Gore & Storrie in Ontario has recently applied this technology to poplar tree plantations for treating reclaimed water). It is the authors opinion that a gravity type system used over crown beds can be economical and efficient. Figure 5 shows a typical cross section of such a bed.

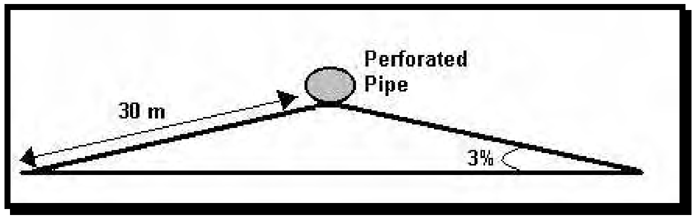

Figure 5 , Sloped Crown Bed design

5.5.3 Ongoing Research (Village of Alfred Pilot Project)

Ongoing research in the field of post wetland polishing is currently taking place at Alfred College of the University of Guelph. The College has constructed a pilot constructed wetland project for the treatment of municipal waste for a small rural community (Village of Alfred). Part of the project includes studying the performance of two types of post-wetland polishing methods, namely phosphorus slag filters, and vegetative filter strip.

The study's main research objectives are:

1) to determine if slag, a by-product of the steel manufacturing process, can be used as an adsorption medium to reduce orthophosphate concentrations in the wetland effluent to below 0.3 mg/l in a sustainable manner. Slag is available in large quantities in Ontario and the steel industry is looking for markets for this product.

2) to monitor the wetland system for 3 years to establish the removal algorithms for each wetland cell for BOD_5, Nitrate and Nitrite, Ammonium and Ammonia, TSS, TKN, TP, $O\text{-}PO_4$ and pathogens.

Proposed Solution for the Permanent Removal of Phosphorus

Phosphorus removal may be achieved in a permanent and predictable manner using a constructed filter composed of an adsorbing media (i.e. clay pellets, peat, blast furnace slag, steel furnace slag, sand). For example, blast furnace slag can remove up to 44g of phosphorus per kg of media *(Sakadevan & Bavor, 1998).* This capacity to remove phosphorus is essentially due to its content of aluminum, iron and calcium oxides.

The final design of an adsorption filter is dependent on the characteristics of the chosen media (hydraulic conductivity, required contact time and porosity). Three loading modes could be used: horizontal flow, vertical upflow and vertical downflow. Filter volumes for a given contact time are similar for both horizontal flow and vertical downflow filters. The choice between vertical and horizontal flow filters will therefore depend on operating and capital costs. For example, it is easier to remove the media in horizontal flow filters, but easier to unclog vertical flow filters. Horizontal flow filters can be vegetated. This allows for the transport of oxygen to the media and thus favours phosphorus adsorption.

Vertical flow filters can be oxygenated by either bringing the water in pulses or by installing an aeration system in the filter. Finally, horizontal flow filters have fewer mechanical components. Andersson *et al*. (1992) mention that there is very limited experience in using vertical upflow filters in large-scale operations. They indicate that wastewater treatment with upflow filters does not seem to yield better performance than downflow filters. Energy requirements and capital costs are much higher for upflow filters.

The above information will have to be taken into consideration to decide if vertical or horizontal flow filters should be used, yet it seems that slow-rate downflow filters would be more appropriate to remove phosphorus from municipal wastewater.

Blast Furnace Slag

One type of adsorption medium readily available in Eastern Ontario is steel furnace slag (SFS). A preferred choice would be blast furnace slag (BFS), a coarse sand-like material produced when limestone, coke and iron ore are fused to produce iron *(Mann and Bavor, 1993)*. Gehlenite ($2Ca0.\ Al_20_3.Si0_2$) is its major component, which could explain its high Langmuir adsorption maxima (44.2 g P/kg of media), as measured by Sakadevan and Bavor *(1998)*.

In 1988 Sakadevan and Bavor performed a phosphorus adsorption study that included 2 steel industry slags, zeolite, and six soil types from different constructed wetland systems in Australia. Blast furnace slag showed to have the highest capacity of those tested with a value of 44.2 g P/kg slag.
While the study performed by Sakadevan and Bavor *(1998)* examined the P removal efficiency of blast furnace slag it did not examine the P transport in saturated slag columns. Tests performed in columns can provide basic information for the design of efficient land treatment facilities. These tests can also be used to study the adsorption isotherms and the effects of P influent concentration on P adsorption, and to determine breakthrough curves and the mobility of P in the slag media *(Lee et al., 1996)*.

The following Figure and Table depict the properties of the slag that was tested as part of the Village of Alfred Pilot Project

Figure 6 , Size and Gradation of Slag Samples

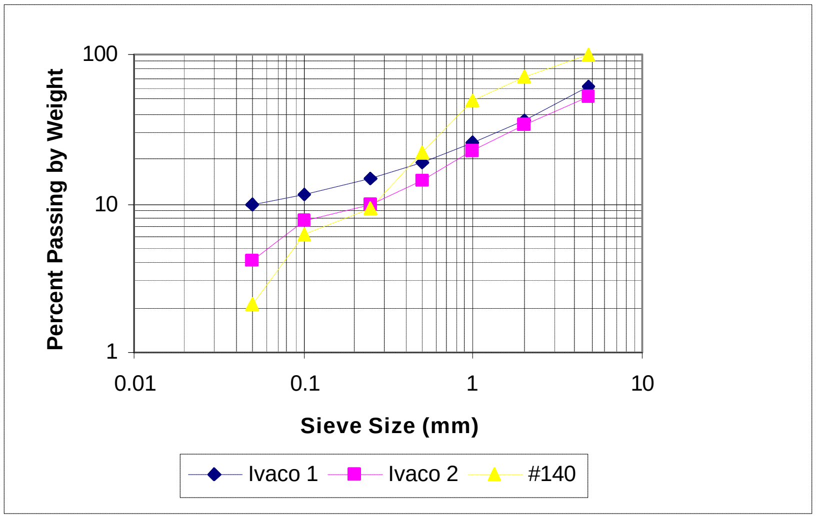

Table 7, Chemical Properties of Slag Samples

		IVACO (1)	IVACO (2)	#140
FeO	%	8.09	9.22	0.83
Al_2O_3	%	2.16	2.09	6.8
CaO	%	36.6	35.8	28.3
As	mg/L	8	8	ND
Se	mg/L	1	1	5
Hg	mg/L	ND	ND	ND
Cd	mg/L	ND	ND	ND
Cr	mg/L	480	548	33
Co	mg/L	ND	ND	ND
Cu	mg/L	84	85	33
Pb	mg/L	32	39	6
Mo	mg/L	16	21	ND
Ni	mg/L	42	43	ND
Zn	mg/L	449	597	8

Calcium, iron and aluminum oxides for the two types of IVACO slag are very similar. This indicates that both slags should have adsorbed approximately the same amount of phosphorus. When comparing the metals content of the IVACO slag to the National Slag Limited #140 type, the metals concentration are higher for the IVACO slag (approximately 10 times higher). It is important to determine the effect of the higher metal concentration. During future column tests, the metal concentration in the leachate will be measured.

Batch Adsorption tests

Phosphorus lagoon effluent concentrations for the Alfred municipal lagoons were consistently below 4 mg/L from 1995 to 1998 *(OCWA, 1998)*. Eight set of experiments were conducted. Adsorption isotherms only hold for the range of test conditions in which the experiments were conducted. Even though the influent phosphorus concentration is expected to be below 4 mg/L, the initial experiments, in 1998, were done at phosphorus concentrations between 500 and 1000 mg/L. The batch tests were conducted at concentrations between 0.1 mg/L and 8000 mg/L. The mass of slag used in the experiments were in the range of 5 to 30 g.

For feed concentrations below 100 mg/L and a mass of slag greater than 5 g, the levels of phosphate left in the supernatant were undetectable. The slag removed too much phosphate and adsorption isotherms could not be calculated. It was suspected that slag type #140 had too small a diameter and if used in a filter it would clog; it was therefore, removed from the remainder of the study. Influent phosphate concentrations were increased to 8000 mg/L for the final tests with the two slag types from IVACO. Preliminary results suggest that the IVACO 2 type of slag has a greater potential for phosphorous adsorption than the IVACO 1 type slag (IVACO 2 type slag had a potential adsorption capacity of approximately 22 g of P /Kg of slag). The slag types from IVACO slag are steel furnace slag, whereas, the slag from National Slag Limited is Blast Furnace Slag, which has a greater potential for phosphorous adsorption (approximately 44 g of P /Kg slag).

Future field work for the project will consist of constructing three in situ filters that will be filled with the selected slag material and operated over several years (minimum 3 years). Inlet and outlet phosphorus concentrations will be monitored 9 times per year to determine the removal efficiency of each filter.

Vegetated Filter Strips

One small component of the Alfred Pilot Project Study includes the construction of vegetated filter strips to determine their filtering and adsorption capacity. Removal rates for various pollutants, including phosphorous, will be determined for various loading rates. The information obtained with the field work portion of the study will help determine the optimum loading rate for filter strips and reasonable removal rates that can be achieved.

NOTE:

Further Information on the Village of Alfred Pilot Project can be found in Appendix C. More information will be provided min the future, in the form of an addendum to this manual, as research progresses on the Village of Alfred Project.

6.0 DESIGN CONSIDERATIONS

6.1 Location

At the site selection stage, the engineer should review all geological maps, topographical maps and if possible aerial photographs (to help identify obstacles such as pipelines, trenches, roads, etc.). Once a preferred site has been selected on paper, in-situ tests should be performed to determine site stratigraphy, physical soil properties, saturated permeability etc. Such tests will help confirm the adequacy of the site and will help in designing the wetland foundation. Although investigative guidelines are given in *ASTM D 420-93 " Site Characterization of Engineering ,Design and Constructions purposes", Vol 04.08, Soil and Rock, Annual Book of Standards*, it is highly recommend that the use of a geotechnical expert be used for this part of the works (see section 6.2)

Sites overlying perched water tables, groundwater recharge zones, or fissured rock must be avoided if the wastewater contains deleterious contaminants. Even if a liner is used, these sites should be avoided to limit the risk to the local water supply. Ideally a constructed wetland should be located in a groundwater discharge zone to minimize groundwater pollution potential Areas that are prone to flooding, such as floodplains, should also be avoided since they may cause a flooding hazard and may be subject to erosion, scouring, sedimentation and high groundwater tables. Geologic hazards such as mine shafts, faults and abandoned wells, that provide a pathway to the groundwater, should also be avoided.

Prior to construction, the advice of an expert with respect to hydrogeological conditions is recommended (see section 6.2). The expert will determine the need for monitoring wells at the edge of the property to measure the potential migration of contaminants and to obtain baseline data for future comparison. **As a minimum, nearby springs and wells should be analyzed to obtain baseline data.**

Since the majority of the construction consists of earth works, proper site topography is crucial. Consideration should be given choosing a site that is flat or gently sloping (less than 5 %). Such a site will make it easier to achieve a proper cut and fill balance. The amount or earth excavated should be enough to construct the cell berms without significant excess. Steep slopes would require significant earth moving activity (including importing earth) and possibly terracing. This would significantly increase the cost of the project.

6.2 Soils

Proper characterization of the soils at the site is critical to the success of a constructed wetland. Soil characterization includes a detailed soil profile, defining the bedrock depth and the groundwater regime. In-situ soils should not be contaminated, should be able to provide a suitable environment for plant growth and should be a suitable construction material. Neglecting this phase of the work would result in increased construction and maintenance cost, poor performance and possible contamination problems.

NOTE:

It is highly recommended that a geotechnical expert be consulted for this phase of the work. The geotechnical expert will be able to determine the permeability of the soil, the depth of bedrock, the groundwater regime and will assess the potential risk for groundwater contamination. Furthermore, the geotechnical expert is familiar with local, provincial and federal regulations and can inform the designer of specific requirements.

The results of the geotechnical study will determine the level of compaction and soil thickness needed to prevent infiltration of groundwater and exfiltration of sewage or whether an impervious liner is required. Physical and chemical tests that are often required prior to design are the following:

Table 8 - Recommended Physical and Chemical Tests

Physical tests (Construction)

- soil profile definition;
- United Soil Classification System (USCS);
- particle size analysis;
- dispersion percentage and/or Emerson Aggregate Tests (EAT)
- Shrink/Swell (Linear Shrinkage or volume expansion); and
- hydraulic conductivity

Chemical Tests (plant growth)

- pH;
- electrical conductivity;
- organic matter;
- cation exchange capacity
- trace metals; and
- phosphorous sorption or phosphorous fixing capacity.

(source : Constructed Wetlands Manual, Volume 1, Department of Land and Water Conservation, New South Wales)

As a rule of thumb, a natural soil with a saturated permeability greater than 10^{-7} cm/sec, a clay content of at least 20% and a plasticity index of at least 15% is considered the minimum requirement for a compacted clay liner required to prevent infiltration and exfiltration. The minimum clay liner thickness should be at least 300 mm. If drying out of the clay is likely during construction, consideration should be given to having a thicker depth of clay (at least 1.0 m). Chapter 7 of the National Engineering Handbook, part 651

Agricultural Waste Management Field handbook (U.S. Soil Conservation Services, Washington DC) provides further information on how to determine the required liner thickness based on the clay's saturated permeability. As mentioned earlier, however, it is highly recommended that the services of a geotechnical expert be used for this part of the works.

If the soil is inadequate, clay can be imported or a synthetic liner can be considered. The cost of the project, however, will increase. Synthetic liners include, rubber membranes, plastic membranes, bentonite clay embedded in a geotextile fabric to name a few. The liner must be strong enough to prevent root penetration and attachment. For example, polyethylene liners with a thickness of 0.5 to 1.0 mm are adequate to protect against root penetration. A geotechnical expert can assist the designer in choosing an adequate liner.

Shallow bedrock at a site will eliminate that particular site from consideration. The bedrock not only provides a pathway for contamination to reach the groundwater, but significantly increases the cost of the project.

During clearing and grubbing work, care should be taken as to properly stockpile the topsoil and protect it from contamination. This soil will be used for top dressing of the cell berms and to create the cell substrate. A minimum of approximately 30 cm of topsoil will be required for the cell floor since the roots and rhizomes of emergent macrophytes usually occupy the top 30 cm of the soil column. The designer must therefore take this topsoil volume into consideration during the cut and fill balance exercise.

6.3 Hydrology

Hydrologic and hydrogeologic considerations include the characterization of surface water and groundwater. Water may enter into a constructed wetland from various pathways such as precipitation, surface flow, groundwater flow and wastewater influent. Improper consideration of these factors may impact the operation and treatment ability of the constructed wetland. For example, if a water balance is not properly computed, the system may dry out during hot dry periods, or may be flooded during wet periods.

When designing a wetland system, a proper water budget is essential. Consideration should be given to rainfall, evaporation and evapotranspiration (generally wetland evapotranspiration and lake evaporation are roughly equal). If the wetland captures surface runoff (such as runoff from a feedlot), it must also be included in the water budget equation. Infiltration however, can be neglected in most cases since impermeable soil (or a liner) would presumably be present.

Choosing average and extreme years are essential in computing a proper water budget. Typically, ten year extremes provide an adequate safety factor (i.e. it would be acceptable for the wetland to dry out or to be flooded once every ten years). The designer however, must choose a design period that will meet his/her requirements or local guidelines.

"Precipitation less evapotranspiration" data is then analyzed using statistical approaches to determine extreme figures. In general, total precipitation is a direct measurement taken by the weather station, whereas potential evapotranspiration is the amount of water that evaporates and transpires from a vegetated surface. For the purpose of design, a figure of approximately 0.8 times class A pan evaporation is used to estimate the evapotranspiration of constructed wetlands. Once the return period data is determined for dry conditions and wet conditions, a water balance can be performed. If statistical data does not include return period data for your design, the following method can be used:

1. Obtain monthly statistical data that includes precipitation and evapotranspiration (at least 10 years of data should be analyzed for the 10 year return period (the greater the years of data, the more accurate the analysis).

2. Determine the yearly precipitation-evapotranspiration for each year. If the wetland only operates in the summer, April to November data should only be used. It can be assumed that the system is full after the spring freshet

3. The data can then be plotted using the Weibull plotting position formula:

   $$P = 100 * m/(n+1). \quad [8]$$

   where P = plotting position (in %),
   m = rank (1 being the greatest precipitation-evapotranspiration), and
   n = number of years.

   For the ten year extremes, the 10% position represents the wet year and the 90% position represents the dry year.

Once the wet extreme and the dry extreme years are found, monthly data (April to November) for those years can be used for the water budget analysis. The water budget should look at the month by month volume of water that is entering the system (precipitation, runoff, influent) and leaving the system (evapotranspiration, effluent). It can be assumed that the system is full after the spring freshet (for seasonal systems only).

If runoff is included in the equation (such as feedlot runoff), the following formula can be used:

$$\text{Runoff volume} = \text{precipitation} * C * A \quad [9]$$

where C is a runoff coefficient and A is the Area.

Runoff coefficients for undeveloped lands (pasture, crops, etc.) can range from 0.15 for sandy soils to 0.4 for clay soils.

The water budget analysis is very important since it will determine if the storage and/or facultative ponds are properly sized, the required freeboard and if the wetland will use up all of the available water prematurely, thus causing the system to dry out. If additional water is required, the designer can try to capture more of the spring freshet, or a well can supply additional water to the system.

6.4 Hydraulics

Wetland hydraulics are an important factor to consider when designing a constructed wetland. They play a role in determining factors such as the retention time and control structure requirements, which are critical factors for a successful wetland design.

Hydraulic residence time is the time that it takes for the waste water to pass through the system. A hydraulic residence time greater than 10 days is considered optimum to ensure that pathogens are reduced by sunlight exposure or natural die off. Hydraulic residence time is defined as:

$$t\,(\text{days}) = \frac{LWnd}{Q} \qquad [10]$$

where L = Length of system -parallel to flow direction (m)
W = Width of system (m)
n = porosity of the bed.
d = depth of submergence (m)
Q= average flow through the system (m^3/day)

The porosity of the bed is defined as:

$$n = V_v/V \qquad [11]$$

Where V_v and V are the volumes of voids and the total volume, respectively.

In a free-surface system the volumes of voids are more or less the volumes unoccupied by vegetation. Typical porosity values range from 0.86 (for bulrushes) to 0.98 (for reeds). Other vegetation values are 0.9 (cattails), 0.94 (woolgrass) and 0.95 (rushes).

As noted in section 5.4, the length to width ratio for marshes should be in the range of 3-5:1 to ensure plug flow conditions and minimize short-circuiting. The pond portion of the system may have ratios as low as 1:1. The wetland shape may be rectangular provided the flow is properly distributed at the inlet.

The depth of submergence for free surface wetland (marsh cell) varies from 10 cm to 60 cm, depending on the type of waste treated and the time of year. During summer months, it is recommended that the operating depth fluctuate between 15 cm and 30 cm with an average of 20 cm. If an aerobic pond is used in a marsh-pond-marsh layout, it should have a minimal depth of approximately 60 cm. Bottom slopes for marshes and ponds should be essentially flat (not greater than 0.02%). Widths must be flat to ensure equal flow distribution .

6.5 Cell Construction

Components of the wetland and pre-treatment system are either a shallow pond or a deep pond. Design and construction techniques used for general farm ponds or small treatment lagoons are appropriate for these types of systems. The designer must allow for freeboard in the design to allow for the accumulation of organic matter (peat) at the rate of 2-3 cm/year. Furthermore a 30 cm additional free board should be allowed for in berm construction to accommodate the 10 year wet period. Berms should have outside slopes of 3:1 and inside slopes no steeper than 2:1. The top of the berms should have a width of approximately 2 m to allow for easy maintenance and to help discourage aquatic mammals from burrowing through them. The designer may consider however, incorporating welded wire vertically in the berm during construction to prevent mammals from burrowing through them and causing failure (wire in the berms is aesthetically more pleasing than placing rip rap on the slopes and also does not inhibit vegetation). The berms should be rolled/compacted and the sides should be mulched and seeded as soon as possible to reduce erosion.

6.6 Control Structures

Control structures are an important part of constructed wetland designs. The basic management of a wetland system consists of manipulating the flow and water level in the system to optimize storage and treatment. Simple methods used for controlling flows and water levels include pumps (for flat sites), flow splitter structures, weirs, inlet tructures and outlet structures.

6.1.1 Pumps

For small systems located on a flat site, the use of pumps is beneficial. Not only will the pumps provide a better flow control, but they can reduce the amount of earth works required to elevate the wetland for gravity flow. For small systems the solution is as simple as using a submersible pump with a timer (to control the flow automatically). A small pumping chamber can be constructed from a polyethylene manhole or if it is drawing water from either the anaerobic lagoon or facultative pond, it can be attached to a floating raft (inner tube) to reduce costs even further. The advantage of these simple pumping stations is that the pumps are inexpensive, can be replaced easily and can be removed prior to freezing.

Figure 7 : Submersible Pump with Timer

6.6.2 Inlet Distribution

At the inlet of a wetland cell, a distribution system is required to evenly distribute the flow along the width of the cell to promote plug flow and minimize short circuiting. If pumps are used to control the flow, the simplest inlet distribution structure is a perforated PVC pipe along the width of the inlet (elevated on concrete blocks- see Figures 8 and 9). This structure is easy to install and maintain and can be removed prior to winter .

Figure 8 - Perforated Pipe Inlet

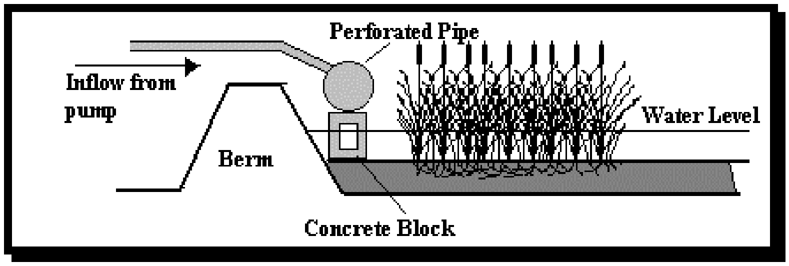

Figure 9 : Perforated Pipe Inlet Distribution

If the influent is supplied by gravity rather than pumps, a flow control mechanism is required. The simplest method for a gravity feed system is to install PVC piping along the inlet with swiveling “T” sections to allow for adjustment of each “T” throughout the length of pipe (see Figure 10). The “T”s are rotated up or down to increase or decrease flows from respective “T”s .

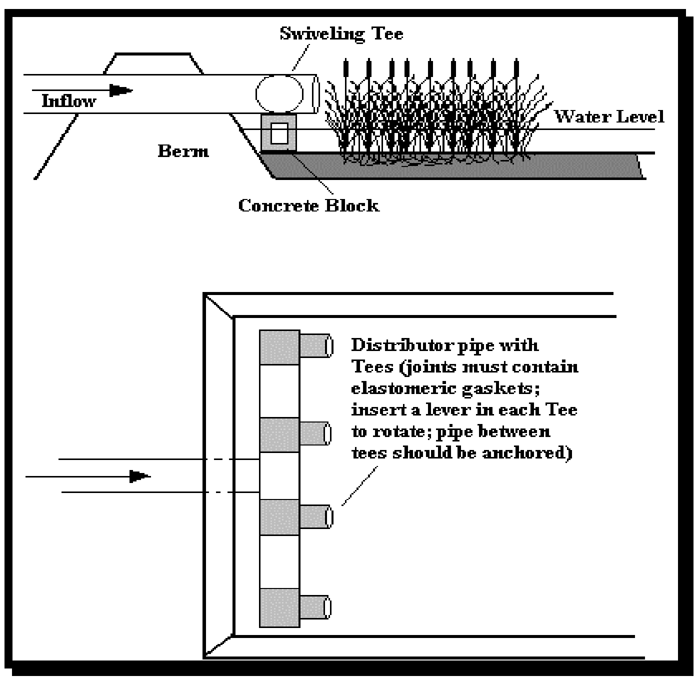

Figure10: Swiveling Tee Inlet Distribution

6.6.3 Weirs

Figure 11: Simple V-notch Weir

Weirs are simple low cost control structures which control water levels and the flow from one wetland cell to another. For small free surface systems (with flows less than 25 m^3/day), the weir can be constructed of a plastic sheet and embedded directly into the wetland berm at the cell outlet. Although this kind of design does not distribute the flow along the wetland width at the outlet, it should not cause significant short-circuiting problems due to the low flows. Dye tests on the Dignard system in 1995 (*Weil et al, 1995*) showed that with a weir type outlet at one end of the cell, short circuiting was not significant (flows were approximately 10 m^3/day). The Dignard system did have an inlet pipe that distributed the flow along the entire width of the inlet.

As an alternative to a weir, some low flow systems may be constructed with the use of an overflow spillway, which consists of a low portion in the berm, covered with an erosion protection mat (either water tolerant vegetation, rip rap or a synthetic cover).

6.6.4 Outlet Control Structures

Outlet control structures are critical in controlling the water level in the wetland cells. For free surface systems, a typical control structure would consist of a chamber with a rotating standpipe (see Figure 12). The wetland would have a perforated or slotted PVC pipe placed in a gravel media along the entire width of the cell to enhance sheet flow in the cell. The pipe would connect to a control box in which the rotating stand pipe would be located. If flows are great, the rotating standpipe can be replaced with a stop log structure.

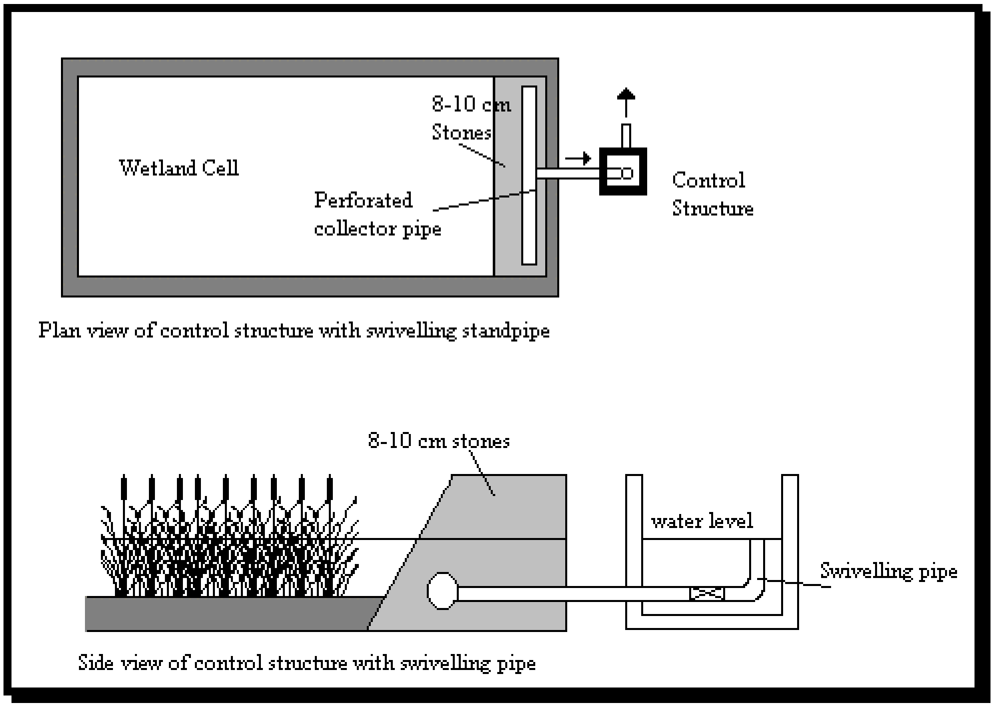

Figure 12 - Outlet Swiveling Standpipe System

6.7 Anaerobic Lagoon and Facultative Pond Design

Sections 5.2 and 5.3 described the requirements for sizing aerobic lagoons and facultative ponds. When designing these two types of ponds, it is important to remember the following points:

- The anaerobic lagoon should be designed to store the wastewater for a minimum of six (6) months.
- They must be impermeable.
- The outside berms should be no steeper than 3:1 and the inside berms should be no steeper than 2:1 (to minimize wave action erosion).
- A freeboard of at least 30 cm should be provided for both the anaerobic lagoon and facultative pond. This will provide a factor of safety for extreme events.
- Accumulation of sediment at the bottom of the ponds should be accounted for in the design. For example, if it is anticipated that 2 cm of matter will accumulate per year and that the pond will be cleaned every 10 years, an additional 20 cm should be allowed for in the pond depth. Consideration should also be given as to how solids will be removed from the pond (see section 6.9)

- Anaerobic lagoons should have a depth of 2.5-5 meters and a width-to-length ratio of 1:3.

- Facultative ponds should have a depth ranging between 0.7-1.8 meters.

- The anaerobic lagoon inlet should be placed at the bottom of the lagoon and the outlet designed as overflow. The inlet and outlet should be positioned as far apart as possible.

- The outlet pipe should have a downpipe of approximately 0.3 m to prevent discharges of surface materials.

- Access to the anaerobic lagoon must be provided to allow periodic dredging of accumulated solids.

6.8 Vegetated Filter Strip Design

Sections 5.5.1 described the requirements for sizing a vegetated filter strip. When designing this kind of polishing system, it is important to remember the following points:

- The filter strip is to be used for the polishing of advanced quality wetland effluent (See section 5.4).

- As a conservative estimate, the application rate should be no greater than 0.05 m^3/hour per m length of filter.

- The length of the filter should range between 45 and 90 m.

- The filter width should be no less than 9 m to allow for the use of harvesting equipment.

- The filter should operate for a two (2) week period followed by a two (2) week rest period (to allow for harvesting). The effluent can be applied continuously over the two week period.

- The filter should only operate when that average daily temperature is above 0°C.

- The filter can operate during periods of rainfall.

- The crop should be harvested every three to four weeks.

- Harvesting equipment should have flotation tires to limit rutting.

- The filter site should be at least one meter above the groundwater.

- The filter slope should range between 1% and 4%.

- The vegetation best suited for a filter strip are grasses with a long growing season, high moisture tolerance, extensive root formation, high stalk density and high tolerance to variation in nutrient levels. Reed canary grass is often chosen for this application (can be mixed with bromegrass to increase palatability). Other recommended grasses are ryegrass and tall fescue.

- Wastewater delivery systems include gated pipe, fan sprays, sprinklers and overflow structures.

6.9 Irrigation System

As mentioned earlier, much literature exists on agricultural irrigation delivery systems. Should the practitioner wish to use irrigation for post wetland polishing, it is strongly recommended that such literature be referenced to make the best use of the technology. Various methods include using spray, gravity (flooding) and drip irrigation.

6.10 Sludge Handling

One aspect of constructed wetland design that is often overlooked is that of sludge handling. In most cases, sludge handling is not a serious concern since it is assumed that sludge will accumulate in an upstream system (settling pond) prior to entering the constructed wetland. Accumulation in the wetland cells will therefore be negligible and removal will take place only once every 10 to 20 years. When designing the upstream settling pond, however, consideration must be given to cleaning out the pond more regularly (5 to 10 years) depending on the accumulation. If the wetland system is to be used to treat septage waste for example, the solids accumulation will be substantial and frequent removal will be required (every 2 years). If, on the other hand, the system is being used for the treatment of holding tank waste, accumulation will take place at a much slower rate because degradation of the solids will still occur in the settling pond (solids from septage waste is already digested, therefore further degradation will be minimal). Many municipal waste stabilization lagoons are dredged infrequently (15 to 20 years). The following is a discussion on sludge handling the designer should take into consideration.

6.10.1 Settling Pond Configuration

The designer must consider that sludge will eventually need to removed. If the operator of the system can afford to shut down the system once every ten years on average, a one cell settling pond may be adequate. If the system, however, must remain in operation, the designer may want to consider dividing the settling pond into two cells so that one could remain in operation while the other is allowed to dry for cleaning. Furthermore, the designer should consider how the cell will be cleaned. If the cell is small enough, the designer may want to make sure that its dimensions allow for mechanical sludge removal from the berms (using a shovel, drag line etc.) The sludge could then be deposited on the berms to dry for future handling. If the pond is too large for sludge removal from the berms, a ramped access into the pond will be required. When designing the pond bottom, the designer will have to consider that machinery will be moving on the floor of the pond.

6.10.2 Composting

Once the sludge has been removed from the settling pond, it can be hauled to a composting site for future spreading on agricultural lands. Composting is the stabilization of organic material through the process of aerobic, thermophilic decomposition. The sludge found at the bottom of settling ponds will only have a solids content of approximately 5% on average. If the pond is allowed to dry enough to allow for the sludge to become a paste type of material (solids content of approximately 20%), removal can be done with mechanical equipment (shovels, loaders, etc.). If the sludge is pumped out of the bottom, the addition of bulking agents will be required. Such agents include woodchips, sawdust, straw etc. The purpose of the bulking agent is to decrease the moisture content, increase the porosity and ensure aerobic conditions during composting. On average, the compost pile must be allowed to stabilize for a period of approximately 90 days before it can be used as a soil additive on agricultural land. One must keep in mind, however, that not all types of compost will be allowed to be disposed of on agricultural lands, and some may need to be directed to landfill sites. The designer should review the proposed design with the Ministry of the Environment.

6.10.3 Sludge Drying Reed Beds

Vertical-flow reed beds consist of a flat bed of gravel topped with sand with reeds growing over it *(Cooper et al., 1996).* They are quite similar to sand drying beds in which a pipe network distributes effluent over the bed and another network of pipes at the bottom of the bed is used for drainage. The reeds develop an intense network of roots in the sand, as well as in the sludge layer that accumulates over the bed *(Mellstrom & Jager, 1994).* The roots of the reeds have two effects: 1) they create channels in the sludge that improve dewatering; 2) they bring oxygen to the sludge layer creating aerobic conditions that will help stabilize and mineralize the sludge. The reeds also eliminate some water by evapotranspiration. Depending on the depth of the sludge layer, the dry solids content can vary from 15-50% *(Kim, 1994).*

The design of sludge drying reed beds is based on the loading of dry solids. Usual recommended values range from 30 to 60 kg dry solids/m^2/yr, but the loading should not be higher than 20 kg dry solids/m^2/yr during the first year. The depth of the bed is usually 800 mm, with 700 mm of 5-10 m size gravel and 100 mm of sharp sand. Sludge can be applied at any time during the year, but lesser frequencies should be chosen during winter months. Freezing and thawing may help to dewater the sludge. Sludge drying reed beds are used in New England (USA), Denmark, the UK and Germany.

The use of reed beds to dewater septage is quite new. According to Michael Ogden *(Southwest Wetlands Group Inc., Santa Fe, New Mexico, USA, Personal communication)*, high solids content waste such as septage waste can be used on reed beds. The septage should first be screened, stored in an equalization pond and the grease should be removed. It seems that the reed bed has a low efficiency to reduce the nitrogen and soluble BOD concentrations. A downstream wetland that would handle the liquid waste, however, would solve this problem. This technique is an interesting alternative to mechanical dewatering, as it not only dewaters the sludge but also stabilizes it. It is also much less expensive.

7.0 CONSTRUCTION AND OPERATION

7.1 Plans and Specifications

The preparation of proper plans and specifications is critical so that the final product will resemble the design. Furthermore, if the plans and specification provide sufficient detail, the owner will have a sound basis for legal recourse should the final product not meet contract specifications. As a minimum, the plans and specifications should outline the following:

- clearing and grubbing limits,
- location of benchmark,
- final grades,
- existing and proposed utilities,
- borrow areas,
- types of structures,
- type of equipment (i.e. pumps, irrigation etc.)
- dimensions,
- berm and structure material,
- bottom permeability,
- control structures,
- undisturbed areas,
- erosion control plan,
- seeding, sodding and planting requirements.

The specifications should also clearly outline the construction and planting period and any restrictions on either site access, completion date (and penalty if any), bonding requirements, testing methods (permeability), plant survival determination (to determine if replanting is necessary), payment method, start-up and acceptance procedures. The designer and the owner should, however, keep in mind that not all minute details can be included in the plans and specifications and that good faith and understanding with the contractor is necessary.

During the tendering process, the bidders should be invited to a site meeting and conference to discuss all aspect of the project. This will help reduce the contractor's misperceptions, specifically since we are dealing with earth works. A detailed site walk-around should be held with all bidders.

7.2 Site Preparation

The best time of the year to undertake construction is during the dry season. This will facilitate the earth works aspect of the job, therefore minimizing the construction time. Prior to constructing the individual components of the wetland system, some site preparation work is required. The following steps should be followed:

- identify the survey benchmark,
- establish site boundaries and identify areas to be protected,
- clear and grub works area,
- remove and stockpile topsoil for later use. Avoid mixing topsoil with underlying material. Protect topsoil from contamination,
- if existing wetlands soil is removed for later use, it should be stored underwater to avoid oxidizing and releasing bound metals or other substances;
- all permeable soil materials, organic matter, rocks, trash or debris should be removed;
- peg out the excavation and fill areas and locate the position of structures. This work should be done with precision and it is therefore recommended that survey equipment be used.

7.3 Anaerobic Lagoon and Facultative Pond

Although lagoons and ponds are relatively simple to build, specific steps must be followed to ensure proper construction. The following basic construction steps should be followed:

- excavate ponds and build berms.
- stockpile excess material if it is needed in the wetland construction (to elevate wetland cell for gravity flow), otherwise, spread excess material adjacent to site.
- if necessary, dewater ponds to construct bottom liner or compact in situ material.
- grading must be carefully checked. Poor grading may lead to poor water level control and plant management;
- check pond bottom and berm permeability (conductivity of $<1x10^{-6}$ cm/sec), is clay liner or compaction necessary? **Consult with Geotechnical Engineer**.
- compacting in situ (or fill) material should be done with proper equipment at optimum moisture conditions;
- manufacturer's instructions should be clearly followed if synthetic liners are used. Caution should be taken not to puncture the liner.
- construct water control structures.
- finish all disturbed areas with 100 mm of topsoil from stockpile area, then seed and mulch.

7.4 Wetland Cells

As mentioned earlier, the dry season is the best time to construct the wetland cells. For this reason, planting may need to be delayed until the next wet season. The following recommended construction sequences are modified from *Hammer's 1994 guidelines*

- excavate cells and build berms (dewater cells if necessary).
- check grading carefully. Poor grading may lead to poor water level control and plant management;
- check cell bottom and berm permeability (conductivity of $<1x10^{-6}$ cm/sec). Is clay liner or compaction necessary? **Consult with Geotechnical Engineer**.
- compact in situ (or fill) material with proper equipment at optimum moisture conditions;
- follow manufacturer's instructions if synthetic liners are used. Caution should be taken not to puncture the liner.
- construct water control structures and inlet distribution/outlet collection piping.
- flood cells to just above top surface of the new floor.
- check grading; check elevations and operation of inlet/outlet piping.
- drain and re-grade or reset pipes and controls as necessary.
- place and level 30 cm of topsoil on floor of the cells.
- check grading; check elevations and operation of inlet/outlet piping and water controls.
- drain and regrade or reset pipes as necessary.
- plant the deeper water pond section - lilies, pondweeds.
- plant the shallower marshes - cattail, bulrush, rush, etc.
- flood cells with clean water or low strength wastewater to just above top surface of substrate or topsoil.
- finish all disturbed areas with 100 mm of topsoil from stockpile area, then seed and mulch
- three weeks after start up, (obvious growth on new plants), raise water level to 5 -10 cm but do not overtop plants.
- six weeks after startup, initiate operation with low strength wastewater or one-half of the design flows.
- three months after startup, begin operation with normal strength wastewater or 100% of the design flow.

NOTE:

Once the cells are constructed, preliminary flooding of the cells is necessary. Flooding will not only be useful in checking grades, elevations and control structures, but it is critical to prevent cracks and leaks in the clay liner and berms.. The cells should be kept flooded until planting.

7.5 Planting and Seeding

The two most popular methods of vegetating wetland cells are planting and seeding. Both methods can be successful depending on the procedure undertaken. Prior to introducing vegetation to the wetland cells, the following preliminary steps should be taken:

- ensure that at least 30 cm of topsoil (or wetland substrate) is placed, uncompacted, on the cell floor.
- ensure that the wetland substrate is level.
- the substrate can be left prepared for some time prior to planting and/or seeding, however it should be protected from erosion and treated for weeds.
- make sure that the wetland substrate is moist (not flooded) just prior to planting (or seeding).

7.5.1 Planting

- optimal planting conditions for cut materials are created by shallow flooding followed by dewatering but not complete drying to leave soft, moist soil conditions.

- plants should be properly stored prior to planting (proper moisture and temperature conditions, proper handling and minimal delay time).

- planting stock should not be dug more than two days before planting and should be stored and transported in a cool, dark, humid environment.

- planting must be done in rows and must run perpendicular to the direction of the flow to improve coverage and reduce channeling, even though it may be easier to operate equipment up and down the long axis of a cell.

- after planting, the cells should be flooded with 1 - 2.5 cm of water (insure that water depths do not overtop cut stalks or the new plantings may die).

- as new growth begins, water levels may be slowly raised but should not overtop the new growth.

- planting materials may also be obtained locally (cattail, reed, bulrush may be found in roadside ditches).

- if roadside ditch or other natural depression material is used, there is a risk of incorporating unwanted vegetation such as Purple Loose Strife into the cells.

- transplanted materials must have at least an 20-30 cm stalk to insure that the stems protrude above the water surface. If mature emergent (cattail, rush, etc.) plants are dug for planting, the stalks should be cut off to similar lengths since tall plants are susceptible to wind-throw until the roots have re-developed secure attachment in the substrate.

- sago or other pondweeds and other submergents are usually planted as tubers, simply weighted with nails and dropped into the water or placed on soft, wet muds at the desired locations.

- planting of emergents (cattail, bulrush and arrowhead) should be done sequentially with the lowest elevations planted first and higher elevations later. Emergent species should be planted in saturated but not flooded soils and allowed to grow stems with leaves that project above planned flooding levels the first season. After stems reach 10-20 cm, water levels can be raised 4-6 cm above the substrate and proportionately increased as plant height increases until desired elevations are reached.

- planting of submergents in the ponds may be accomplished best in standing water

- after all planting is finished, the water level should be gradually raised to normal operating elevations as the plantings grow higher but water levels must not overtop new growth during the first growing season. Emergent plants are not as susceptible to drowning after first growing season or in waters with relatively high dissolved oxygen content.

- water levels should be slowly and gradually increased to support erect, upright growth of submergent and floating leaf plants.

- submergent plants should not be allowed to dry out (maintain shallow overtopping).

- flooding the new submergent plantings with turbid waters or waters with low dissolved oxygen will stress and perhaps cause mortality of these plants.

- inappropriate water levels can inhibit establishment and growth of desirable wetlands plants, however unsuitable levels can be used to control prolific growth and spread of weedy, terrestrial species. Flooding may retard invasion by terrestrial opportunists and deeper flooding may retard undesired colonization of additional areas by planted wetland species.

7.5.2 Seeding

- hand or natural seeding is less expensive but may be less reliable for starting the new plant community since the germination rates of many wetlands plant seeds are often <5% per year.

- large quantities must be collected and distributed due to poor germination rates.

- whether hand or natural seeding is used, the pond should be shallow flooded in late winter and early spring and dewatered at the onset of warm weather to establish warm moist mud conditions.

- careful monitoring and regulation of water levels at or just below the pond bottom is important to maintain the proper soil moisture conditions for germination and sprouting.

- after the new growth has reached 10-12 cm, water levels should be raised to 1-4 cm above the substrate to inhibit or kill terrestrial species but should not overtop wetlands plants.

NOTE:

Once the vegetation has started growing, care must be taken to ensure that weeds are controlled. Due to the lack of dense vegetation at the start of a wetland cell, weeds may invade the cell and become a major problem, specifically Purple Loose Strife in Ontario. Owners and Operators can use the following methods to control weeds:

- buying seed that is certified as being free of weed seeds,
- timing activities to minimize weed germination,
- light cultivation (scarification) or surface disruption prior to planting,
- manual removal (often the most effective method if action is taken before the problem gets out of hand),
- competition (planting a dense crop of wetland vegetation will inhibit weed growth)

Pre and post emergent herbicides are available for weed control, but their use is discouraged because they are toxic and they can have a negative effect on the local wildlife.

7.6 Vegetated Filter Strip

Vegetated filter strips are well graded fields planted with a specific type of vegetation. When constructing the strip, consideration should be given to the following points:

- slopes should be within a range of 1% to 4%.

- the strips cross-section should be flat to prevent the formation of concentrated flow paths, which would lower the removal efficiency.

- the width of the filter strip should be sufficient to permit the use of harvesting equipment (minimum width of approximately 9 m).

- crops best suited for vegetated filter strips are grasses with a long growing season, high moisture tolerance, extensive root formation, high stalk density and high tolerance to variation in nutrients levels. Furthermore, palatability should also be considered when harvesting for forage is planned. Reed canary grass has a very high nutrient uptake capacity and yields a good quality hay. Mixing reed canary grass with bromegrass may increase palatability. Other suitable grasses include ryegrass and tall fescue. Grasses that bunch, such as timothy and orchard grass, are not recommended for filter strips unless used in a mix with grasses that forms a dense sod.

- up to two years could be required in to establish vegetation with adequate density. During that establishment period, care should be taken to properly fertilize the seeded vegetation and to control weeds proliferation.

- preconditioning can enhance nitrogen removal during start-up conditions in cool temperatures. Preconditioning consists of applying wastewater to the vegetated filters for approximately 4 hours the day before start-up, which results in pre-activation of a biological growth on the grass/soil media.

7.7 Construction Supervision

Construction supervision of the works is critical to the success of the project. Inspection of the works should be done regularly to ensure that tasks are executed according to the plans and specifications. Timing of inspections is critical during construction. The following inspection schedule is recommended (see table 9 next page):

Table 9 - Recommended Site Inspections

When to Inspect	What to Check
Site establishment	Site Security, conform to site boundaries, compound, stockpile areas, access, benchmark.
Set Out	Conforms to plan
After rainfall events	Erosion, need for repairs, dewatering during construction
Excavations	Levels, safety of open excavation, stockpile of surplus material, quality of material (clay, topsoil,etc.)
Embankments and cell floor	Proper material, compaction, proper side slopes.
Geosynthetic (if required)	Installed according to manual, smooth profile free of roots and vegetation, pegging and anchor trenches.
Prior to placing substrate	Is cell floor level and sealed?
Structures	Foundation preparation, location, materials, levels, alignment, fully functioning.
Pipework	Levels, bedding, alignment and grade
Planting, seeding	depth and moisture of substrate, weeds, vegetation density.
Completion	Quality of finish
Warranty Period	Defects such as erosion, settling, plant die off, burrow holes in berms.

Modified from Constructed Wetlands Manual, Volume 1, Department of Land and Water Conservation, New South Wales)

7.8 Operation

Natural treatment systems are relatively simple to operate especially when gravity flow is incorporated in all aspects of the design. The simplest gravity flow control system in the wetland cell is either a simple weir or elbow pipe structure. Fairly precise water level control in the wetland cells is important in enhancing growing conditions for desirable plant species and controlling weeds if necessary.

- On average the normal operating depth for a wetland cell should be 10-20 cm in each FWS wetland and 0.7 -1.0 m in the pond wetland. Proper water depth and careful regulation is a critical factor for plant survival during the first year after planting.

- Flooding often causes more problems for wetland plants during the first growing season than too little water if the water has low dissolved oxygen content. Submergent and floating leaf species (in the pond area) require actual flooding soon after germination or planting because most depend on buoyant structures and water pressure for physical support to achieve an upright growth form. The objective of water level management is to create unfavorable conditions for terrestrial species by shallow flooding or saturating the soil but not to stress wetlands species by deep prolonged inundation.

- Shallow flooding (2-5 cm) can limit invasion of weedy or terrestrial species once the wetlands plants have stems higher than 8-12 cm (it is absolutely essential that stems and leaves of desirable species project well above the water's surface to avoid drowning new or even older established plants).

- Gravity flow is often preferred over mechanical devices. In small systems however, the use of small submersible pumps may be economical and may provide a precise method of flow control. The control can consist simply of a submersible pump attached to a floating device (i.e. innertube) on the facultative pond. The pump would direct flow to the wetland inlet, and then gravity flow would take over. Pumps can also be used to convey flow from the anaerobic storage lagoon to the facultative pond using the same principle of a floating pump. The pumps should draw water from the upper 0.6 m of the lagoon or pond in order to minimize the discharge of suspended solids.

- After the first year of operation, the operation and maintenance typically consists of walking around the berms at least once a week to check for any erosion, seepage or animal damage. The berms should also be mowed weekly and water quality samples collected as needed

- Routine weekly inspections are necessary to ensure appropriate flows through the inlet distributor and outlet collector piping as well as leaks in the piping itself.

- Flow distribution within cells should be occasionally inspected to detect channel formation and short-circuiting and be corrected by planting vegetation or filling soil in any channels.

- Grass and wetlands vegetation should be checked at least once a week to identify any visible signs of stress or disease such as grass yellowing, chlorosis, leaf damage, etc. Should stress or disease be noticed, a specialist should be consulted.

- Pumps, valves, "T" fittings, etc. should be checked at least once each week to ensure that pumps and all piping are operating properly (i.e., check for clogging and make sure that the flow coming out of each "T" fitting is the same).

- The wetland should be operated with clean water or very low-strength wastewater for the first month after planting. During the fifth week, initiate operation with one-half strength wastewater or with one-half the design flows and continue for three months. After the end of the fourth month, begin operation with full-strength wastewater or with full design flows. Check proper operation of all piping, pumps and water control structures and monitor vegetation.

- If a vegetated filter strip is used, it should operate for a two (2) week period followed by a two (2) week rest period (to allow for harvesting). The effluent can be applied continuously over the two week period.

- A vegetated filter strip should be cut and harvested on a regular basis. Care should be taken to limit rutting from the harvesting equipment. It is recommended that specialized flotation tires be used on the harvesting equipment. Mowing every 3 to 4 weeks in the growing season is required for proper field maintenance.

7.9 Monitoring

To determine the effectiveness of a natural system, careful monitoring is required. Accurate measurement of the wastewater volume is crucial for proper computation of pollutant removal. Furthermore, water quality samples should be taken on a regular basis at various points along the system. This will help monitor the effectiveness of individual components.

Since the system performance is evaluated on the basis of removal/transformation of pollutants, influent and effluent monitoring provides the basic data for comparison. The user should therefore measure the inflow from the storage lagoon, the runoff due to precipitation and the outflow from the system. Flow measurements can be done by using simple V-notch weirs or if pumps are used, by knowing their time of operation. Precipitation runoff can be estimated by using a rain gauge and the following equation:

$$\text{Runoff } (m^3) = \text{Rain gauge reading (m)} \times \text{Area } (m^2) \times \text{Runoff coefficient.}$$

Sampling frequency may vary for different types of wastewater, however, the minimal requirement should be at least once a month over a 2 to 3 year period. Weekly sampling is recommended since it will provide more reliable data. Hammer recommends in his 1994 guidelines that as a minimum, a composite 24-hour sample be taken on a week day once per month and one grab sample once a month.

With respect to the filter strip, routine monitoring should include the wastewater application rate, runoff rate, runoff quality (including biological and chemical oxygen demand, suspended solids, total dissolved solids, total nitrogen and total phosphorus, pH and sodium adsorption ratio). When pathogens in the effluent are a concern, faecal coliforms should also be monitored.

Background weather conditions including temperature, humidity, and rainfall should be collected since these data would be useful to assess the impact of meteorological factors on the system performance.

8.0 CASE STUDIES AND ADDITIONAL INFORMATION:

Further information and case studies on natural systems for rural applications can be found in the following appendices:

Appendix A	Dignard Dairy Farm Constructed Wetland System (Case Study)
Appendix B	Cost benefit analysis of using constructed wetlands for rural applications.
Appendix C	Village of Alfred Demonstration Project (Case Study).
Appendix D	Swine Manure Treatment Strategies to Reduce Hauling and Disposall Costs
Appendix E	Design example for septage waste.
Appendix F	Food Processing Waste Treatment using Constructed Wetlands

REFERENCES

Andersson, C., M. Tendaj and M. Rothman. 1992. Filtration at Bromma *Sewage Treatment Plant.* Water Science and Technology 25: 59-66.

Barrington, S. 1991. *Characteristics of Livestock Manures.* Proceedings: Canadian Agricultural Research Council, National Workshop on Land Application of Animal Manure. June 11-12, 1991. Ottawa.

Brix, H, 1987, *Treatment of wastewater in the rhizosphere of wetland plants - the root zone method*, In water Science Techonology, 19.107-118

Brix, H. 1994. *Use of Wetlands in Water Pollution Control: Historical Development, Present Status, and Future Perspectives*. Journal of Water Science and Technology 30(8):209-223.

Brown, D.S. and S.C. Reed 1994. *Inventory of Constructed Wetlands in The United States*. Journal of Water Science and Technology 29(4):309-318.

CH2M Gore & Storrie Ltd, 1998, *Treatment Wetland and Poplar Tree Technology*, Short Course Manual , September 16-18, 1998, Toronto, Ontario, Canada

Chaubey, I., D.R. Edward, T.C. Daniel, P.A. Moore Jr. and D.J. Nichols. 1994. *Effectiveness of Vegetative Filter Strips in Retaining Surface-Applied Swine Manure Constituents.* Transactions of the ASAE. Vol 37(3): 845-850.

Cooper, P.F. *et al*. 1996. *Reed Beds and Constructed Wetlands for Wastewater Treatment.* WRc Swindon, UK

Department of Land and Water Conservation, New South Wales, 1998, *Constructed Wetlands Manual, Volumes 1 and 2*, National Library of Australia

Dillaha, T.A., R.B. Reneau, S. Mostaghimi, and W.L. Magette. 1987. *Evaluating Nutrient and Sediment Losses from Agricultural Lands: Vegetative Filter Strips.* United States Environmental Protection Agency, CBP/TRS 4/87.

Hamilton, H., P.G. Nix and A. Sobolewski. 1993. *An Overview of Constructed Wetlands as Alternatives to Conventional Waste Treatment Systems*. Water Pollution Research Journal of Canada 28(3):529-548.

Hammer, D.A. 1994. *Guidelines for Design, Construction and Operation of Constructed Wetlands for Livestock Wastewater Treatment*, Proceedings from “Constructed Wetlands for Animal Waste Management; Lafayette, IN, 1994”.

Hammer, D.A. 1995. *Water quality improvement functions of wetlands. In Encyclopedia of Environmental Biology*. Academic Press, Inc. San Diego, CA. **3**: 485-516.

Hammer, D.A. 1997. *Creating Freshwater Wetlands, 2nd Edition*. CRC Press Inc. Boca Raton, Fla.

Higgins, J., Hurd, S. and C. Weil. 1999. *The Use of Engineered Wetlands to Treat Recalcitrant Wastewaters.* 4th International Conference on Ecological Engineering.

Kadlec R.H, Knight, R.L, 1996, *Treatment Wetlands*, Lewis Publishers, New York

Jenssen, P.D., T. Mæhlum and T. Krogstad. 1994. *Potential of Constructed Wetlands for Wastewater treatment in Northern Environments.* Journal of Water Science and Technology 28(10):149-157.

Lee, S. H., Vigneswaran, S., and K. Bajracharya. 1996. *Phosphorus Transport in Satruated Slag Columns: Experiments and Mathematical Models.* Water Science and Technology 34:153-160.

Lemna Corporation 1994. *Innovations in Lagoon-Based Treatment*. Retention Times, Spring/Summer, 1994. (Promotional literature).

Magmedov, V.G. and L.I. Yakovleva. 1994. *The Experience of the CIS on Using Constructed Wetlands for Waste Water Treatment*. European Water Pollution Control 4(2):22-25.

Mann, R.A. and H.J. Bavor. 1993. *Phosphorus Removal in Constructed Wetlands using Gravel and Industrial Waste Substrata.* Water Science and Technology 27: 107-113.

Metcalf & Eddy, Inc. 1991. *Wastewater Engineering, Treatment, Disposal, and Reuse*. Third Edition.: 982-992.

Mitchell, C. 1996, *Pollutant Removal Mechanisms in Artificial wetlands*, Course notes for the IWES 96 International Winter Environmental School, Gold Coast, July

Ontario Clean Water Agency, 1998, *Annual Operating report, Village of Alfred Treatment Lagoon*, unpublished

Ontario Ministry of the Environment, Guidelines on the Design of Water and Sewage Treament Plants, Chapter 21,1991

Overman, A. R., and D.W. Wolfe. 1986. *Overland Flow Treatment of Wastewater at Florida State Prison.* Journal of Water Pollution Control Federation. Vol. 58, no.9: 903-910.

Payer, F.S., and R.R. Weil. 1987. *Phosphorus Renovation of Wastewater by Overland Flow Land Application.* J. Environ. Qual., Vol. 16, no. 4: 391-397.

Payne, V.W.E., 1983. *Lagoon-Pond-Grassed Filter for Treating Wastewaters*. ASAE summer meeting presentation, paper no. 83-4067.

Reed. S.C. *et al*. 1988. *Natural Systems for Wastewater Management and Treatment.* McGraw-Hill Book Company, New York, 532 pp.

Reed, S.C., R.W. Crites and E.J. Middlebrooks, 1995, *Natural Systems for Waste Management and Treatment*, 2nd Ed, New York, McGraw-Hill.

Sakadevan, K. and H.J. Bavor. 1998. *Phosphate adsorption characteristics of soils, slags and zeolite to be used as substrates in constructed wetland systems*. Water Resources 32:393-399.

South West Wetlands Group, *Food Processing waste treatment using constructed wetlands*, 1997, unpublished.

Toombs, M. R. 1997. *Evaluation of Vegetative Filter Strips (VFS) to Treat Beef Feedlot and Dairy Yard Runoff in Ontario.* Paper presented to the CSAE/SCGR at the joint conference with the Canadian Society for Civil Engineering, May 28 - 30 at Sherbrooke, Quebec

U.S. E.P.A, 1994, *Guide to Septage Treatment and Disposal*, Office of Research and Development, Washington D.C.

U.S. E.P.A, 1995, Office of Research and Development, Washington D.C.

U.S. National Research Council, 1996, *Use of Reclaimed Water and Sludge in Food Crop Production*, National Academy Press, Washington D.C.

Vymazal, J. 1993. *Constructed Wetlands for Wastewater Treatment in Czechoslovakia: State of the Art. In Constructed Wetlands for Water Quality Improvement,* ed. G.A. Moshiri, 255-260. Pensacola, FL**.**

Weil, C. *et al*. 1995. *Dignard artificial wetland: interim report*, R&TT, Collège d'Alfred, Alfred, Ontario.

Weil, C. *et al*. 1997. *Dignard artificial wetland: interim report*, 1996. R&TT, Collège d'Alfred, Alfred, Ontario.

White, G., Kuginis, L., Beharrell, M. & Young, C., 1996, Urban stormwater management, in water, pp.48-52: July/August

Young, R. A., T. Huntrods, and W. Anderson. 1980. *Effectiveness of Vegetated Buffer Strips in Controlling Pollution from Feedlot Runoff*. J. Environ. Qual., Vol. 9, no.3:483-487.

APPENDIX A

DIGNARD DAIRY FARM WETLAND SYSTEM

CASE STUDY

**DIGNARD DAIRY FARM WETLAND
CASE STUDY
(By: Claude Weil, P.Eng, Alfred College)**

INTRODUCTION

Point source and diffused pollutants of agricultural origin are a growing concern. Treating them while keeping healthy margins in this industry is a challenge. Constructed wetlands are being more and more carefully engineered using validated models as opposed to the empirical design relationships which were available earlier. The Dignard dairy farm is located outside the town of Embrun, near Ottawa (Ontario, Canada). Because of its location near a creek, the farm is subject to the scrutiny of local residents concerned over its impact on the environment.

The Dignard herd is composed of approximately 190 animal units (100 cows, 60 heifers aged 0-4 months, 30 heifers aged 4-7 months and 75 heifers aged 8 months and over). The operation produces wastewater from three sources: runoff from a solid manure pile, stormwater runoff from a 0.75 ha exercise yard (used by 60 heifers), and milkhouse wastewater (the washwater used to clean and sanitize the milk pipeline and bulk storage tank). Solid manure, mixed with milkhouse wastewater, is stacked by an air piston onto a concrete pad. Prior to construction of the wetland system in 1994, runoff from the solid manure pile was stored in an anaerobic lagoon and periodically spread on cropland. The runoff from the feedlot was not collected. The owners required a system that would treat the liquid runoff from both sources without the need for spreading. Otherwise, separate systems would have been required for handling liquid and solid manure; increasing equipment and labour costs. An engineered free water surface (FWS) wetland system was constructed in 1994 to treat runoff from the manure stack and the 0.75 ha. cattle yard for the Dignard dairy farm.

WETLAND DESIGN

The old anaerobic lagoon continues to be used to collect manure and milkhouse water from the barns. Effluent from this lagoon is pumped into a facultative pond where it joins runoff from the exercise lot, which has flowed over an overland flow field.

Because large volumes of runoff were to be treated, a natural system incorporating two FWS wetland cells was chosen. In 1994, the wetland/pond/wetland system was designed and constructed, according to the guidelines advocated by Donald Hammer of Purdue University (Hammer, 1994) to treat the effluent from the manure runoff lagoon and the cattle yard during summer months. The layout of the Dignard Wetland is shown in Figure 1.

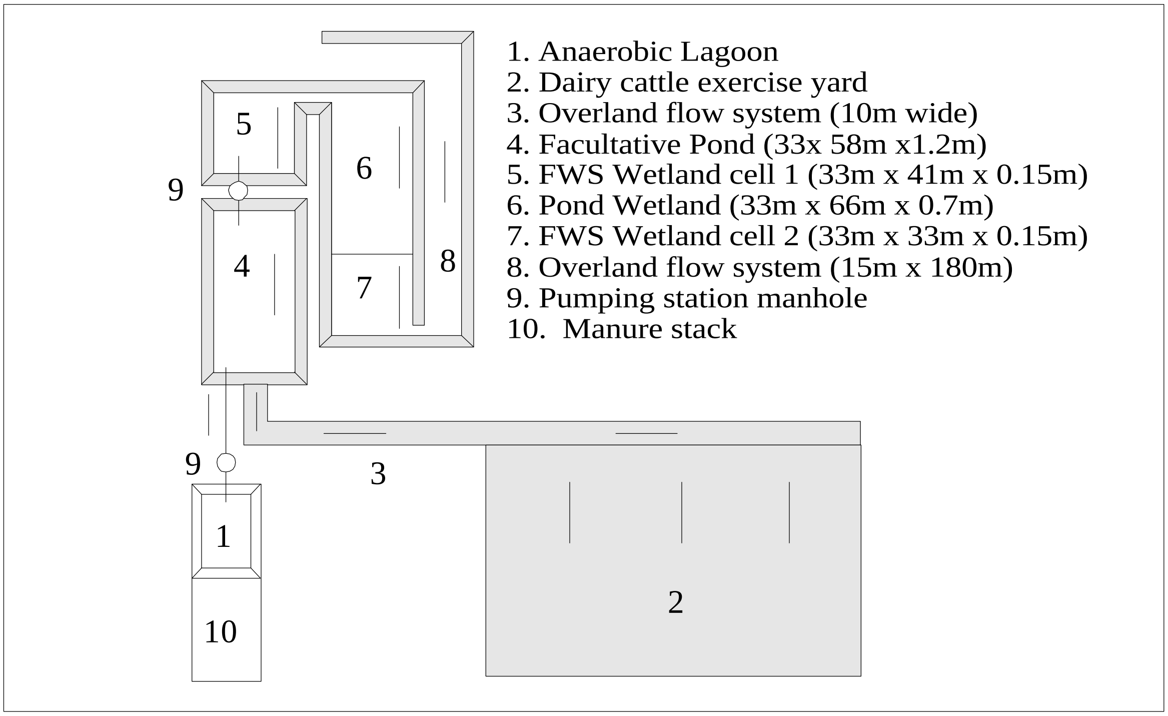

Figure 1: Dignard Engineered Wetland System

Hammer (1994) found that biochemical oxygen demand (BOD) levels above 300-500 mg/L would stress wetland cells "perhaps even to the point of failure". On the Embrun site, BOD in the anaerobic lagoon was measured as ranging from 539 to 1720 mg/L prior to construction of the wetland system. Therefore, pretreatment was required between the anaerobic lagoon and the wetland system. A facultative pond was selected for this purpose. Facultative ponds not only provide high BOD removal (more than 88% according to Gloyna & Tischler (1981)), they can accept shock loads and efficiently mix wastes of different chemical and physical properties so as to feed a uniform effluent to subsequent wetland cells. The facultative pond also provides flow equalization to accommodate climatic fluctuations. It acts as a "drought" water reserve in July and August to prevent excessively dry and/or sluggish flow conditions and provides storage of yard runoff from October 1st to April 30th.

Effluent from the facultative pond flows into FWS wetland cell #1. This is followed by a pond wetland, and finally by FWS wetland cell #2.

The wetland cells were planted with cattails in the fall of 1994 and in the spring of 1995. The system was put into operation the summer of 1995. In establishing the plants, it was determined that the best results were achieved in the fall by breaking the heads of cattails and disseminating the seeds over the wet wetland topsoil.

An overland flow grass filter strip polishes effluent from the second FWS wetland cell. This grassed filter has a 0.3% slope. It is composed of topsoil underlaid by native clay. It also behaves as a slow rate infiltration system to optimize phosphorus removal by adsorption on the clay base. A stringent requirement for a total Kjeldahl nitrogen (TKN) mass loading not to exceed 3 kg/ha/day, used to determine the required area of the system, governs the design in order to produce an effluent of such a quality that direct discharge in a nearby creek could be possible. The average detention times are 177 days in the facultative pond, 11 and 19 days in FWS#1 and FWS#2 wetland cells respectively, and 88 days in the pond wetland.

Design of natural system in Embrun

D.2.1 Design of stabilization pond

Design function:

Facultative pond design is based on the removal of BOD_5. With detention times in the order of weeks, most suspended solids will also be removed. The pond depth ranges from 1.2 to 2.5m. Facultative pond operation is based on the production of oxygen by photosynthetic algae and surface reaeration. The oxygen is used in the aerobic digestion process of the upper layer. Anaerobic digestion occurs in the bottom layer. The CO_2 produced in the bottom layer serves as a carbon source for the algae. The pond serves the following functions:

- To intercept feedlot runoff and collect lagoon effluent
- To mix lagoon and feedlot effluents into a homogeneous liquid waste which is stabilized
- To reduce suspended solids, BOD_5, bacteria, total nitrogen and total phosphorus. The BOD_5 is to be reduced to less than 400 mg/l. In the process faecal coliform contents will be reduced by at least 90% because of the extended detention time.
- To provide a reserve of effluent to keep the wetland operating during a dry year with a 10 year return period. This minimum reserve (drought reserve) is kept from May 15th until September 15th.
- To ensure even discharge into the wetland system so as to optimize its performance by minimizing disruption to chemical, biological and physical conditions.

Facultative pond surface area based on influent BOD_5 quality, C_e = 1720 mg/l

Schedule of Operation

The anaerobic lagoon contains up to 255 days of storage; this provides flexibility for the starting date of treatment into the wetland system. The period of treatment of anaerobic lagoon's contents transferred daily into the facultative stabilization pond is 132 days, from May to September.

Daily flow = 11 m^3

BOD_5 mass loading into stabilization pond:	18.9 kg/day (as per highest measured concentration, 1720 mg/L)
TKN mass loading into stabilization pond:	2.4 kg/day (as per highest measured concentration, 219 mg/L)

Past September 30th, any runoff and snowmelt from the feedlot will be stored in the stabilization pond which by then would contain 0.6m of waste (pump level).

<u>Method based on natural reaeration of the pond:</u>

Method 1. - Using a 100 kg/day/ha. allowable loading rate (Reed et al., 1988) for summer usage, pond area A is:

= 1892 m^2

$$A = \frac{1720 mg/L * 11.0 m^3/day * 10^{-6} kg/mg * 10^3 L/m^3 * 10^4 m^2/ha}{100 kg/day/ha}$$

Such a pond should produce an effluent with a BOD_5 less than 30 mg/l (Reed et al., 1988). This is better than the 400mg/l target effluent quality.

Method 2. - Using the plug flow model:

$$\frac{C_e}{C_o} = \exp\left[-k_p t_d\right]$$

where C_e = effluent BOD_5 concentration, mg/L
C_o = influent BOD_5 concentration, mg/L
k_p = plug flow first-order reaction rate for a given T, $days^{-1}$
t_d = hydraulic residence time, days

For a depth of 1.2 m, a side slope of 1:1, V   2000 m^3

t_d = 2000/11 = 182 days
k_{20} = 0.129 d^{-1} (Reed et al., 1988)
k_{13} = 0.129 x 1.09 (13-20) = 0.071 d^{-1}
C_e = 1720 mg/l x $e^{-0.07 \text{ x } 130}$
0 mg/l

In reality, short circuiting and limited surface aeration will yield an effluent of lesser quality. As mentioned earlier, a BOD_5 effluent of 400 mg/l rather than 30 mg/l will be assumed as a safety measure. The facultative stabilization pond must have a surface area of 1892 m^2 or more for a 1.2 m depth of flow. Use of surface aerators may significantly reduce the pond size as shown below.

Surface area provided for facultative pond for a 1.2 m operating depth:

66 m × 33 m = 2178 m^2

Conservative estimates of effluent quality entering wetland:

BOD_5	400 mg/L
TKN	219 mg/L × 0.80 = 175 mg/L

Method using aerators based on Metcalf and Eddy (1991)

The pond could be significantly reduced in size with the use of surface aerators. Assuming no lack of dissolved oxygen, a pond less than half this size could yield an effluent with a BOD_5 less than 400 mg/l. A sample calculation follows, based on an assumed decay coefficient, k_{13}.

k_{13} = 0.071d^{-1} (assumed)

Dispersion coefficient, D = 0.5

BOD_5 removal = 80% (C_o = 1720 mg/l, C_e =400 mg/l)

$k_{13}t$ = 2.4 (from Wehner and Wilhelm equation)
0.071d^{-1} t = 2.4
t = 34 days

Depth of flow = 1.2 m

Minimum pond volume = 34 d x 11 m^3/d = 374 m^3

Mass loading = 1720 mg/L × 11 m^3/day × 10^{-3} = 18.92 kg/day

Approximate surface area = $\frac{374 \text{ m}^3}{1.2 \text{ m}}$ = 311.6m^2

Surface loading = 18.92 kg/day × 10 000 m^2/ha = 607.2 kg/ha./day

$311.6\ m^2$

Oxygen mass transfer M required from an aerator (design of aerobic - anaerobic stabilization ponds, Metcalf & Eddy, 1991):

$$M = 2\ kg\ O_2/kg\ BOD_5 \times 18.92\ kg\ BOD_5/day$$
$$= 37.84\ kg/day$$

Transfer rate = 22 kg O_2/kW/day (typical aerator - Metcalf and Eddy, 1991)

$$\text{Power Requirements} = \frac{37.84\ kg/day}{22\ kg\ O_2/kW/day} = 1.72\ kW$$

A 2 kW aerator would ensure adequate surface reaeration.

The mechanically aerated pond is substantially smaller. Wind aerators may be used in which case, oxygen transfer rate could be lower. Should the facultative stabilization pond not perform as expected, surface aeration could be incorporated into the daily operation.

D.2.2 Design of wetland/pond/wetland/overland flow system

For design purposes, it is assumed that 11 m^3 of effluent from the stabilization pond is pumped daily into the wetland/aerobic pond/wetland system. The actual flow through the wetland system will be adjusted to the weather pattern and the strenght of the stabilization pond effluent.

Section D.1.2 indicated that the TKN surface area loading in wetland/aerobic pond/wetland systems may be 3 kg/ha/day. The allowable TKN surface area loading for overland flow systems is 30-40 kg/ha/day.

An allowable TKN loading of 3 kg/ha/day is selected for the wetland/aerobic pond/wetland/overland flow system. It provides for a rather conservative design. However incorporating the overland flow system into the treatment process has the effect to reduce the size of the wetland/aerobic pond/wetland system, the expensive component of the system. Basically, not enough information is reported in the literature to allow for higher TKN loadings.

Daily TKN loading: $175\ mg/L \times 11\ m^3/d \times 10^{-3} = 1.92\ kg/d$

$$\text{Total surface area} = \frac{1.92\ kg/d \times 10\ 000\ m^2/ha}{3\ kg/ha/d} = 6416\ m^2$$

a. Wetland/pond/wetland system

Area supplied by wetland/pond/wetland = 66% of 6416 m^2

$6416\ m^2 \times 0.66 = 4234\ m^2$

Wetland area = 50 % of 4234 m^2 = 2117 m^2

Area of each wetland cell = 2117 m^2/2 = 1059 m^2

Dimension of each wetland cell: 33 m × 33 m

Aerobic pond area = 50% of 4234 m^2 = 2117 m^2 at a 0.7 m operating depth
Dimension of aerobic pond cell: 66 m × 33 m

Overall size of wetland/pond/wetland:

length: 132 m
width: 33 m
aspect ratio: 4:1

b. Overland flow system

Surface area of filter = 34% of 6416 m^2 = 2181 m^2

Dimensions: 15 m x 145 m

Note that 11 m^3/d is loaded on the overland flow system over one hour. The system is allowed to rest until the next day.

D.2.3 Design of overland flow system for feedlot runoff

This filter is located along the filter. Treatment is based on the filter width.

Volume to be treated in 1 day: .6m^3/1m wide strip (10 year storm, duration 6 hours)

Application rate per unit width, q = .1m^3/1m hour

hydraulic loading rate:

$$L_w = \frac{qPa(100cm/m)}{Z}$$

where L_w = hydraulic loading rate, cm/day
q = application rate per unit width of the slope, m^3/(h . m) = .1
Pa = application period, h/day = 6
Z = slope length, m

For Z = 10m (10m wide strip)

$$Lw = \frac{.1 \times 6 \times 100 \text{ cm/m}}{10} = 6\text{cm}$$

Equation D.8 allows the prediction of the effluent quality for BOD_5:

$$\frac{C_z - C}{C_o} = A\exp(-aZ / q^b)$$

where C_z = C_{10} = effluent BOD concentration at point Z = width of filter = 10 m
c = residual BOD at end of slope
= 5 mg/L
C_o = BOD of applied wastewater, 500 mg/L
Z = slope length, m
q = application rate, m^3/(h.m) = .1
a,b = empirical constants

Using a graphical solution (Reed et al. 1988) of equation (D.8):

C_{10} - 5 / C_o = 0.20

C_o = 500 mg/l

C_{10} = 85 mg/l at 10 m along the lateral slope (equivalent to width of filter)

Further treatment is provided in the wetland system taking into consideration that runoff events from the feedlot will only be significant in the spring and fall, before and after which the natural system is used for treating the lagoon contents. Thus, the natural system is used sequentially for the treatment of the feedlot runoff and the contents of the lagoon.

Filter strip treatment width:	10m
lateral slope:	2%
longitudinal slope:	0.2%

D.2.4 Estimated effluent quality from proposed system

The literature (Hammer, 1992; Reed et al., 1988) as discussed in section D.1 indicates that the following effluent quality at the overland flow system outlet is achievable:

BOD_5 < 20 mg/L
TN < 20 mg/L

TP < 25 mg/L
FC < 100 organisms/100mL

D.2.5 Summary of Dimensions

1. Facultative stabilization pond:

   Length: 66 m
   Width: 33 m
   Operating depth: 1.2 m

2. Wetland/aerobic pond/wetland/overland flow system:

   1st wetland:

   Length: 33 m
   Width: 33 m
   Operating depth: 0.1 m

   Aerobic pond:

   Length: 66 m
   Width: 33 m
   Operating depth: 0.7 m

   2nd wetland:

   Length: 33 m
   Width: 33 m
   Operating depth: 0.1 m

   Overland flow system:

   Length: 145 m (actual = 180 m)
   Width: 15 m
   Longitudinal slope: 0.3 %

3. Overland flow system treating feedlot runoff:

   Width: 10 m
   Lateral slope: 2 %
   Longitudinal slope: 0.2 %

POLLUTANT REMOVAL MECHANISMS IN WETLAND CELLS

The two FWS wetland cells consist of 0.15 m deep basins and are lined with clay to limit exfiltration. A layer of soil was placed on top of the clay, and in this cattails were planted. A low flow rate is applied so that a shallow depth is maintained.

Settleable solids are removed by sedimentation. Sedimentation lowers BOD and removes particulate forms of phosphorus and nitrogen from the wastewater. A nutrient rich sludge is formed on the wetland floor. The macrophytes supply oxygen to the sludge zone through their roots, thereby promoting aerobic digestion of the pollutants by microorganisms. Macrophytes also act as physical supports for microorganisms. Bacteria and other microorganisms attach themselves to the plants, forming a "biofilm" surrounding the plant from the water surface to the wetland floor. As water passes through the thick growth of macrophytes, it is exposed to the living biofilm, which filters pollutants and degrades them.

Dissolved nutrients are also removed in the wetland cells. The main removal mechanism for dissolved nitrogen is microbially mediated nitrification/denitrification. Firstly, ammonification takes place; in this process organic nitrogen is converted into ammonium. Nitrification (oxidation of ammonia nitrogen) occurs under aerobic conditions: bacteria convert ammonium (NH_4^+) into nitrite (NO_2^-) and nitrite into nitrate (NO_3^-). Significant nitrification occurs above 5 to 7°C. Denitrification occurs under anaerobic conditions: nitrate is converted into nitrogen gas (N_2) which is released into the atmosphere.

Dissolved phosphorus is removed by adsorption, complexation and precipitation with dissolved minerals and by peat accretion (accumulation of organic matter). Its ultimate removal mechanism is burial.

WETLAND OPERATION

The Dignard engineered wetland system treats a total of approximately 1500 m^3 of wastewater over 150 spring and summer days, a period during which biological reactions are accelerated by warm temperatures. Influent wastewater is stored in fall and winter. The treatment system is designed to operate as follows:

a. Feedlot runoff is intercepted and treated in an overland flow system or grassed swale ("3" in Figure 1), which is designed to reduce BOD to below 85 mg/L.

b. Runoff from the manure pile is collected in the existing anaerobic lagoon ("1" in Figure 1), where it is stored from October 1st to April 30th.

c. The overland flow system and the anaerobic lagoon both feed the facultative pond ("4" in Figure 1) in which BOD is reduced to below 400 mg/L. Anaerobic lagoon effluent is pumped daily (at an average rate of 11 m^3/day) into the facultative pond between May 1st and September 30th. Pumping continues until the anaerobic lagoon is empty.

d. Between May 1st and September 30th, effluent from the facultative pond is pumped into the FWS wetland/pond wetland/FWS wetland train ("5", "6" and "7" in Figure 1) at a rate adjusted as a function of evapotranspiration from 10.5 m^3/day to 29.2 m^3/day. These rates are adjusted on a monthly basis the first of each month based on the water level in the facultative pond. Design effluent BOD concentration out of the second wetland cell is less than 100 mg/L.

e. The overland flow system ("8" in Figure 1) completes the treatment train. This overland flow system is an efficient nitrogen and phosphorous remover when the forage crop planted on it is harvested. Target effluent quality is: BOD < 20 mg/L, TKN < 20 mg/L, total suspended solids (TSS) < 25 mg/L and total phosphorus (TP) < 1 mg/L.

Hydrological considerations were not neglected. Using 52 years of rainfall and evaporation data, extreme dry and wet seasons were selected for water budget calculations based on a normal distribution.

A “wet” season is a season (May 1st to September 30th) during which the cumulative precipitation minus evaporation is closest to a quantity that will be exceeded only once during a 10 year return period. A “dry” season is one where this will be exceeded all but once during the same return period. This analysis was performed to ensure that during a dry season the influent waste flow will be great enough to counter losses due to evaporation. This will prevent die off of some of the aquatic plants, which would occur during a prolonged period without moisture. During a rainfall event, BOD and TKN loadings increase due to increased flow rates from the exercise area. Wastewater inflow rates are set to ensure that loadings do not exceed design criteria. Submersible pumps connected to timers are located between the anaerobic lagoon and the facultative pond as well as between it and the wetland cells ("9" in Figure 1). Flow proceeds through the remainder of the system by gravity.

PERFORMANCE OF THE SYSTEM

The Dignard engineered wetland system has performed beyond expectations over the first three years of operation. Table 1 presents average pollutant concentrations at the outlet of each component of the wetland system during the 1996 and 1997 seasons. During the 1997 monitoring season, little water accumulated on the filter strip. For this reason, only a groundwater tube was sampled only once, and no sample was taken on the filter strip. Overall performance of the system was similar to 1996 for BOD, but slightly lower removals were obtained for TKN and TP.

Table 1
Average pollutant concentrations at the outlet of the wetland system components (mg/L)

	BOD		TKN		N-NO_3		N-NO_2		TP	
	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
Anaerobic Lagoon	2567	1153	883.5	421.3	0.27	0.07	0.51	0.40	90.4	66.6
Feedlot runoff	97.4	24.9	167.7	14.3	0.04	0.16	0.17	0.09	47.7	8.7
Facultative pond	215.5	122.6	101.8	79.1	0.11	0.12	0.14	0.08	17.0	19.6
FWS Cell #1	168.1	71.3	91.3	66.8	0.08	0.11	0.10	0.11	13.8	20.0
Pond Wetland	44.2	42.9	38.7	32.6	0.50	0.11	0.37	0.08	7.16	12.41
FWS Cell #2	33.3	32.8	19.7	26.5	0.09	0.10	0.16	0.21	4.27	9.07
Mid-Point Filter-strip	4.40	NA	2.23	NA	0.11	NA	0.05	NA	0.04	NA
End of Filter-strip	3.10	NA	2.83	NA	1.38	NA	0.13	NA	0.07	NA

Table 2 shows the average cumulative reductions in pollutant concentrations for the three operating years. For the 1998 operating season no samples were taken at the outlet of FWS Cell #2 or at the filter strip. Removal rates decreased slightly from 1996 to 1997, but increased again in 1998.

Table 2
Average Cummulative Reduction in Pollutant Concentrations

	BOD (%)			TKN (%)			TP (%)		
	1996	1997	1998	1996	1997	1998	1996	1997	1998
Facultative Pond	91.6	89.4	87.2	88.5	81.2	88.2	81.2	70.6	75.1
FWS Cell #1	93.5	93.8	96.0	89.7	84.1	92.6	84.7	70.0	79.2
PondWetland	98.3	96.3	96.9	95.6	92.3	95.8	92.1	81.4	86.2
FWS Cell #2	98.7	97.2	NA	97.8	93.7	NA	95.3	86.4	NA
End of Filter-strip	99.9	NA	NA	99.7	NA	NA	99.9	NA	NA

Phosphorus removal rates decreased the most over the three year period (92.1% to 86.2%). According to Kadlec & Knight (1996), the startup period for a wetland can extend over varying periods of time, ranging from 1 to 5 years. During this period, performance for phosphorus removal can be expected to decrease until it reaches a steady state. Adsorption produces the highest amount of phosphorus removal in the initial years of operation. Once the adsorption sites have been exhausted, phosphorus removal rates start to decrease.

A better method of evaluating the true performance of the treatment wetland system is to determine the pollutant kinetic removal rate constants. This involves keeping track of the inlet and outlet concentrations of each pollutant passing through the system per day. By developing a databank of kinetic rate constants it not only allows for a better assessment of the system's performance, it also facilitates comparison among systems and may be used to determine parameters for future designs.

KINETIC RATE CALCULATIONS - METHODOLOGY

The data collected included weekly BOD, TKN and TP concentrations at the outlet of each lagoon, pond and wetland cell. For the purpose of the kinetic rate constant calculations, the concentrations of these parameters were assumed to vary linearly between sample times. Concentration values for days when samples were not taken were estimated (e.g., the TKN concentration on May 16 was measured as 63 mg/L and on May 23 was measured as 70 mg/L; the concentration was assumed to increase by 1 mg/L each day).

Pollutant concentrations were also measured after rain events in runoff from the cattle exercise yard and at the outlet of the filter strip. Since there was limited data for these locations, averages were used for the purpose of the calculations. Using a Campbell Scientific data logger equipped with several gauges, hourly data was tabulated for precipitation, air temperature, water temperature and depth of each treatment cell.

Initially, flow rates between the first FWS wetland cell and the pond wetland, and also between the second FWS wetland cell and the grass filter were measured using weirs. In 1995, it was found that debris collecting across the V notch could alter the readings.

To perform a water balance on the facultative pond, all inputs and outputs were quantified. Inputs included pumped flow from the anaerobic lagoon, runoff from the exercise yard and precipitation. Outputs included evaporation, exfiltration and pumped outflow to FWS Cell# 1. Due to lining of the cells with reworked clay with extremely low permeability, infiltration was assumed to be zero for all cells. Runoff from the feedlot was estimated using the SWWM4 runoff module, which utilizes the Horton model to estimate infiltration (Huber & Dickinson, 1988).

The following site information, measured prior to construction in 1993, was used for the SWMM4 simulation: hourly precipitation; feedlot area (0.75 ha); saturated hydraulic conductivity (0.23 mm/hr); asymptotic infiltration rate (10 mm/hr); infiltration decay rate (0.00115 sec^{-1}); average depression storage (6.8 mm); Manning’s roughness coefficient (0.02); and average feedlot slope (0.01). Once the SWMM calculation was conducted and hourly exercise yard runoff volumes were estimated, evapotranspiration was the only remaining unknown and was calculated hourly by:

$$ET = P + Q_{P1} - Q_{P2} + R - (S_n - S_{n-1}) \quad (1)$$

where: ET = evapotranspiration (m^3);
P = direct precipitation (m^3);
Q_{P1} = Pumped flow from anaerobic lagoon (m^3);
Q_{P2} = Pumped flow into marsh # 1 (m^3);

R = Runoff from cattle exercise yard (m^3);
S_n = Storage volume in pond at end of hour (m^3); and
S_{n-1} = Storage volume in pond at end of previous hour (m^3).

This value of ET was then converted into mm/hr and used for all other treatment cells. For marsh 1, the volume at each time step was calculated in the following manner:

$$V_1 = V_0 + P + Q_{P2} - ET - Q_{OUT} \qquad (2)$$

where: V_1 = the volume at the end of the time step;
V_0 = the volume at the beginning of the time step;
Q_{OUT} = cell outflow, calculated using a V-notch weir equation: $Q_{OUT} = 4968H^{5/2}$; and
H = height above weir (m)

The inputs and outputs from the pond wetland and the FWS cell#2 were calculated in a similar fashion.

Linear plug flow reactor of first order reaction kinetics were used to determine the kinetic rate constants for BOD, TKN and TP. The following equation was used to determine the first order volumetric rate constant for the degradation of the various pollutants:

$$\frac{(C - C^*)}{(C_i - C^*)} = \exp(-k_v t) \qquad (3)$$

where: C = concentration of the pollutant, mg/L
C_i = concentration of the pollutant at the inlet, mg/L
C^* = background concentration of the pollutant, mg/L
τ = residence time of a volume of wastewater in the wetland, days
k_v = the first order volumetric rate constant for its degradation, $days^{-1}$

The following background concentrations were used in the kinetic rate constant calculations: C^*_{BOD} of 8 mg/L, C^*_{TP} of 2 mg/L and C^*_{TN} of 10 mg/L was used for the TKN calculations. The values are based on recommended values by Payne Engineering and CH2M Hill (1997) for sizing animal waste treatment wetlands. TKN recommendations were not given by Payne Engineering and CH2M Hill (1997) so the total nitrogen (TN) values were used.

and the hydraulic residence time is given by:

$$\tau = \varepsilon Ah/Q \qquad (4)$$

where: ε = wetland porosity (0.95 for a FWS wetland)
A = wetland surface area, m^2
h = average water depth, m
Q = the flow rate through the wetland, m^3/day

The constant k_v, used in such models, can be related to temperature using the Arhennius equation as follows:

$$k_T = k_{20}\ ^{(T-20)} \qquad (5)$$

Where: k_{20} = kinetic rate constant at 20^0C,
= Arhennius coefficient,
T = water temperature, C
k_T = kinetic rate constant at water temperature T, C

In this paper, the Arhennius coefficients used were 1.06 for BOD (Reed et al. 1995), 1.05 for TN (Kadlec and Knight, 1996), and 1.00 for TP (Kadlec and Knight, 1996).

KINETIC RATE RESULTS

Table 3 includes, for the period of May 23rd to August 27th, 1996, the following information for each component: mean daily inflow and outflow rates, mean daily temperature and the kinetic removal rates for BOD, TKN and TP.

Table 3: Summary of BOD, TKN and TP mass balance (May 23, 1996 to August 27, 1996).

	Facultative Pond	FWS cell # 1	Pond Wetland	FWS cell #2	Overland Flow
Mean daily inflow rate (m^3/day)	15.50	21.49	15.83	4.45	0.09
Mean daily outflow rate (m^3/day)	21.49	15.83	4.45	0.09	0.37
Mean daily water temperature (^{0}C)	14.90	15.68	16.78	16.67	N/A
BOD					
Mean daily influent loading (kg/day)	28.98	4.57	2.56	0.187	0.0024
Mean daily effluent loading (kg/day)	4.57	2.56	0.19	0.002	0.0011
Mean daily removal (kg/day)	39.65	2.24	2.34	0.160	0.0013
Mean kinetic rate constant, k_{20} (yr^{-1})	4.6	11.6	7.5	8.8	N/A
Load reduction within cell (%)	84.2	43.9	92.7	98.7	53
Cumulative load reduction (%)	84.2	91.2	99.4	99.9	99.9
TKN					
Mean daily influent loading (kg/day)	10.54	2.20	1.47	0.163	0.0021
Mean daily effluent loading (kg/day)	2.20	1.47	0.16	0.002	0.0010
Mean daily removal (kg/day)	10.69	0.50	1.08	0.133	0.0011
Mean kinetic rate constant, k_{20} (yr^{-1})	4.0	5.4	5.1	25.4	N/A
Load reduction within cell (%)	79.2	33.2	88.9	98.7	50.6
Cumulative load reduction (%)	79.2	86.1	98.5	100.0	100.0
TP					
Mean daily influent loading (kg/day)	1.22	0.38	0.232	0.029	0.0006
Mean daily effluent loading (kg/day)	0.38	0.23	0.029	0.002	0.0000
Mean daily removal (kg/day)	0.59	0.10	0.112	0.018	0.0006
Mean kinetic rate constant, k_{20} (yr^{-1})	3.1	8.4	3.5	16.4	N/A
Load reduction within cell (%)	69.2	38.4	87.5	92.7	94.0
Cumulative load reduction (%)	69.2	81.0	97.6	99.8	100.0

Payne Engineering and CH2M Hill (1997) recommend certain parameter values for the sizing of animal waste treatment wetlands. These recommended parameters are for FWS wetlands and can only be compared with the calculated FWS wetland values for the Dignard treatment system. Based on an operating depth of 0.3 m and a porosity of 0.95, Payne Engineering and CH2M Hill (1997) recommend using 77.2, 49.1, and 28.1 yr^{-1} for BOD, TN, and TP, respectively. The kinetic rates constants calculated for the Dignard wetland are lower than the values recommended by Payne Engineering and CH2M Hill (1997). The Dignard values range from 10 to 58% of the recommended values for sizing animal wastewater treatment wetlands. The lower values could be a result of the longer detention times in the Dignard system (i.e., detention time in the facultative pond is 177 days and 88 days in the pond wetland). Although the kinetic rate constants were lower than anticipated, the wetland system performed well with overall removal efficiencies consistently greater than 86%.

CONCLUSIONS

The treatment performance of the Dignard constructed wetland was high for the 1996, 1997, and1998 seasons. In 1996, the average BOD, TKN, and TP at the system outlet were 3.1 mg/L, 2.83 mg/L and 0.07 mg/L respectively, well below the target levels set at 20 mg/L, 20 mg/L, and 1mg/L. This represents overall concentration reductions of more than 99.7% for these pollutants across the treatment system. The removal rates achieved by the facultative pond alone were 91.6%, 88.5%, and 81.2% respectively for BOD, TKN, and TP. However, it is the wetland cells and the subsequent verland flow filter which allowed target levels to be met. In contrast to BOD and TKN pollutant reductions, phosphorus reductions percentages decreased over the three years (92.1% to 86.2%). The Dignard wetland has proven to be an effective method for treating the dairy farm wastewaters. Further studies will be conducted at the wetland to observe changes in phosphorus removal efficiencies.

REFERENCES

Gloyna, E.F. and L.F. Tischler. 1981. Recommendations for regulatory modifications: the use of wastewater stabilization pond systems. Journal WPCF Vol. 53(11):1559-1563.

Hammer, D.A. 1994. Guidelines for design, construction and operation of constructed wetlands for livestock wastewater treatment. Proceedings of a workshop on constructed wetlands for animal waste management. Purdue University, Lafayette, Indiana.

Huber, W.C. & R.E. Dickinson. 1988. Storm water management model, version 4: user's manual.

Kadlec, R.H. & R.L. Knight. 1996. Treatment wetlands. CRC Press, Boca Raton, Florida.

Payne Engineering and CH2M Hill. 1997. Constructed Wetlands for Animal Waste Treatment. A manual on performance, Design, and Operation with Case Histories.

Reed,S., Crites, R., and J. Middlebrooks, 1995. Natural Systems for Waste Management and Treatment. 2nd Edition. McGraw-Hill, NY.

APPENDIX B

COST-BENEFIT ANALYSIS FOR A CONSTRUCTED WETLAND IN EASTERN ONTARIO

COST-BENEFIT ANALYSIS FOR A CONSTRUCTED WETLAND IN EASTERN ONTARIO, CANADA

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Keywords: Manure management, Dairy, Manure runoff, Artificial wetland, Constructed wetland, Cost/benefit analysis, Ontario, Canada.

Summary

On-farm constructed wetlands are currently being developed as environmentally sound solutions to decontaminate runoff water emanating from manure storage and feedlot yards. Although the efficacy of the water treatment technology is important, it is also important to evaluate the cost of implementing the technology. This paper presents an analysis of the costs and benefits associated with the choice of the wetland technology compared to using the alternative of spreading the runoff onto cropland. This study is based on a functional wetland operating since 1995 on a dairy farm in Eastern Ontario. All the costs of financing, operating and maintaining the wetland, including depreciation, have been taken into account to estimate the annual cost, which is adjusted to 1997 Canadian dollars.

The total annual cost of this structure is estimated at $5,220, while the alternative of spreading the same runoff volume on land would cost $2,286 more per year. Annual depreciation on the investment represents $2,015, the interest service is $1,961, the operation and maintenance $737 and the loss of crop land is evaluated at $507. A realistic economic lifespan of 30 years has been attributed to the wetland based on comparable structures. Other components have been attributed appropriate economic lifespans. In terms of payback period, the initial investment of $54,090 for the wetland would be paid in slightly more than 7 years. It appears that the wetland technology may be one of the best low-cost choice in Ontario to de-pollute contaminated farm runoff waters before they are allowed to re-enter the natural system. A simulation of the costs of updating the existing wetland systems with a nutrient irrigation pad is presented.

Introduction

A few constructed wetlands have been put into operation on farms in recent years in Ontario and Québec. Many more are appearing on the drawing board. These structures are currently being developed as water-treatment solutions to either decontaminate runoff water, or to process excess liquid manure from large animal operations on the farm. Although the efficacy of the water treatment technology is important, it is also important to evaluate the cost of implementing the technology. This paper presents an economic analysis of the costs and benefits associated with the choice of the wetland technology compared to using the typical alternative of spreading the runoff on cropland.

A surface-flow wetland system was constructed in 1994 on the Dignard Dairy Farm in Embrun (Ontario, Canada). The system was gradually brought to full operation during the summer of 1995, after the establishment of the emergent vegetation. This type of constructed wetland was a first in Eastern Ontario, and one of the very few wetlands in operation on Ontario farms. After three years of operation, performance of the wetland have met all expectations. Clean waters from the finishing strip and meadow are allowed to renter the environment into the nearby stream at the end of the treatment process.

The purpose of the Dignard wetland system is to treat runoff waters from three distinct sources on the farm. Farmstead runoff is now more often recognised as an environmental concern, especially with the increase in the size of animal operations. Although the runoff waters are only slightly contaminated, the sheer volume that is produced annually poses a potential hazard to aquatic systems, especially since average rainfall in the region reach almost 900 mm per year.

The alternative for the owners, that would also be acceptable to the conservation of the environment, would have been to spread very large volumes of diluted wastewaters onto the land. This paper analyses the costs and benefits associated with the choice of wetland technology, compared with the alternative of spreading runoff waters onto the land.

THE DIGNARD CONSTRUCTED WETLAND

The Dignard wetland essentially acts as a natural water treatment process that removes pollutants from the runoff waters emanating from three distinct sources on the farm, all related to animal production. The contaminated wastewaters come from:

(i) runoff from a solid manure pile;
(ii) milkhouse washwaters; and
(iii) stormwater runoff from a 0.75 ha feedlot yard.

Before the wetland system was put into service in 1995, runoff from the solid manure pile was stored in a earthen lagoon and periodically spread on cropland. The runoff from the feedlot was simply not collected.

The owners wanted a system that would efficiently treat all the runoff waters, saving the costs associated with their handling and spreading on land, while creating a naturally appealing environment close to the farmstead. The system has been designed for a dairy operation composed of approximately 190 animal units. The feedlot yard is used by only 60 heifers.

The Dignard average herd is composed of 100 cows, and 165 heifers of which

- 60 are of age 0-4 months,
- 30 are of age 4-7 months, and
- 75 have 8 months and more.

Description of the Dignard Constructed Wetland

The wetland system is designed to operate during the growing season of the aquatic plants, usually from early May to the end of September. During the rest of the year, the runoff is stored in an earthen storage lagoon. The *lagoon* is sized such as to store all the runoff and precipitation waters over the winter period. As well as providing some primary treatment, it acts as a buffer, regulating the flow during the summer months, especially when dry weather could compromise the level of water in the shallow wetland cells, with adverse effects on the emergent vegetation. A facultative *pond* follows in line, fed by a transfer pump from the lagoon. This pond plays a vital role in decreasing the high biological oxygen demand (BOD) and total nutrients (TN) of the lagoon water that could otherwise harm the wetland plants.

Then, during the growing season, waste water from the facultative pond are fed to a first shallow *emergent marsh* (10-15 cm deep) densely filled with cattails. From that point in the system, all flows proceed by gravity. Wastewaters are allowed to enter an *aerobic pond* (70 cm deep) at the end of the first marsh, which is followed by a *second emergent marsh* also densely covered with cattails. An *overland flow system* (a filter strip) polishes the effluent from the second wetland cell. Runoff waters, now essentially pure, are then free to flow toward the nearby creek via a ditch.

Transfer from the lagoon to the facultative pond, and from the facultative pond to the first marsh is done by two electric pumps installed in covered manholes, and automatically activated by electric timers. A distribution line, made of plastic plumbing parts, spread the incoming flow evenly to the front of the first emergent marsh. The wetland system in itself, along with its berms, occupies slightly more than one hectare.

CONSTRUCTION COSTS OF THE DIGNARD WETLAND

The largest costs were incurred with excavation, hauling of soil and shaping of the wetland cells. Topsoil had first to be removed and piled to the side of the construction site. Excavation of the facultative pond began in the fall of 1993, and was finished in the summer of 1994. The subsoil from the excavation was hauled by trucks in position to raise the future cells, and to erect the berms. Shaping of the wetland cells, and replacement of the topsoil followed in late summer 1994. Aquatic plants from nursery stocks were planted the following spring, to vegetate the cells before the system was allowed to slowly begin treatment for the remainder of summer 1995. Repair work was also done on the structure in 1995, prior to the launch. The wetland system has now been functioning flawlessly since 1995. The professional costs to research, design, coordination, and supervision of this construction project, as well as to plant the cells, are not included in this schedule, as they were offered in kind by the many partners. However, typical engineering fees and supervision charges must be included to the construction costs, for a realistic analysis.

DIRECT CONSTRUCTION COSTS (Weil, 1996)		
Removal of topsoil	Aug. 93	$2,436
Removal of topsoil	July 94	$2,397
Excavation of facultative pond	July 94	$4,815
Hauling of soil from facultative pond	July 94	$4,275
Shaping the cells, berms and replacing topsoil	July to Sept. 94	$14,180
Cost of nursery stock plants to vegetate the cells	June 95	$2,500
TOTAL		$30,603

Repairs made in 1995

Some repairs were required after the first winter. The facultative pond needed an extra berm, and some reshaping was done between the cells ($1655). The vegetation on the finishing filter strip had to be re-established twice; uneven settling and too shallow a slope causing severe ponding. The reshaping of this area cost $1572. Total repairs in 1995 amounted to $3227 (Weil, 1996).

Flow control systems

Two pumping stations are located within the wetland system. These stations are manholes made of 900 mm polyethylene tubes laid on concrete bases, covered with locked steel covers. Each manhole harbours an electric pump, controlled by 24-hr timer, and connected to a PVC pipe. A separate electrical service from the farm (100 amps) had to be provided, raising the costs substantially. Weirs are V-notched panels placed at the end of each cell to regulate the flow through the system.

The two submersible effluent pumps are HP Hydromatic model OSP33 that have been rated at about 9 m^3/hr. Although actual retail price to farmers is $435 each (Pers. Comm, Nov. 1997), they were bought at about $300 each in 1995.

FLOW CONTROL SYSTEM COSTS - 1995 (Weil, 1996)	
Manholes, geotextile, riprap, and backhoe	$2,574
Pipe work and weirs	$2,246
Electrical contract	$2,557
Two HP electrical pumps	$600
TOTALS	$7,977

Typical engineering charges

Since the Dignard Wetland built as a prototype artificial wetland, special technical and scientific studies had to be performed by the professional staff at Collège d'Alfred and the South Nation River Conservation Authority. These professional charges are not normally incurred. Nevertheless, every constructed wetland must be custom designed, the soil evaluated and proper plans and permits acquired. Normal engineering fees and building site supervision must be estimated and built into the construction costs. Based on a similar wetland constructed in the Montréal (Qc) area, professional fees, including design and supervision, were estimated at 25% of the construction budget.

SUMMARY OF CONSTRUCTION COSTS

Direct construction costs	$30,603
Repairs made in 1995	$3,227
Flow control systems	$7,977
Actual construction costs	$41,807
+ Design & supervision (25%)	$10,452
TOTAL construction costs	$52,259

Actualisation of the construction costs

To establish the proper basis for comparison, all costs incurred in previous years have to be adjusted to 1997 dollars. Since agricultural services and goods do not generally follow very closely the composite price index (valid for consumers goods), the best approach is to determine what would have been the cost of construction of the same system in 1997, in Eastern Ontario. Updated machinery costs were obtained from the same contractor. The weighed increase of costs from 1993-4 is only 2.9%. All construction costs were updated using this increase (next Table), except for some specific costs (like the pumps, and design/supervision charge) for which specific values are known.

ADJUSTMENT OF CONSTRUCTION COSTS FOR 1997			
	Original costs	Adjustment factor	Costs 1997
Direct construction costs	$30,603	2.9%	$31,490
Repairs made in 1995	$3,227	2.9%	$3,321
Flow control systems:			
Construction materials	$2,574	2.9%	$2,649
Plumbing, piping, weirs	$2,246	2.9%	$2,311
Electrical	$2,557	2.9%	$2,631
Pumps	$600	1997 price	$870
Actual construction costs	$41,807		$43,272
+ Design & supervision (25%)	$10,452		$10,818
Total costs:	$52,259		$54,090

ANNUAL COST OF THE WETLAND SYSTEM OPERATION

The annual cost of financing, operating and maintaining the wetland system was calculated as follows. The initial capital investment was broken down into components, each assigned a realistic depreciation schedule. Interests on the capital investment have also been calculated based on current Ontario farm lending interest rate in late 1997. Annual operating costs were estimated for the maintenance of pumps and berms. Once every 10 years, each of the two shallow marsh cells would also have to be cleaned up, hiking the annual costs further.

Depreciation of system components

In order to calculate the annual capital cost to owning the wetland system, its initial construction costs, adjusted to 1997, must be broken down into similar components, which are assigned an estimated economic lifespan (useful life). Since constructed wetlands are still a novelty in Canada, no genuine experience is available on their actual rate of degradation with the passing years. Although it may possibly be 50 years before the present wetland exceeds its useful life, especially if routine maintenance are duly performed, a realistic and conservative economic lifespan must be assigned. An estimated lifespan for the wetland system has therefore been derived from comparable structures such as earth lagoons and berms. Manure platforms, runoff storage lagoons and silos all have been traditionally assigned an economic life of 30 years (CRÉAQ, 1991). Therefore, a conservative useful life for the wetland has been set to 30 years.

Some concerns may arise as to the accumulation of phosphorus compounds at the bottom of the wetland cells, which may hamper the P-removal effectiveness after a period of operation. It is believed that the periodic dredging of the first shallow cell will replenish the adsorption capacity of the system, and extend the useful life of the system.

The pumps, plumbing network and weirs were assigned an economic lifespan of 10 years, based on comparable farming equipment. Air pistons used to stack manure onto platforms and rowcrop sprayers have economic life estimated at 10 years (CRÉAQ, 1991). Electrical system was given the same lifespan as in farm buildings serviced by electricity: 30 years (CRÉAQ, 1991).

The depreciation method used is the straight-line method, which is most commonly used for farm management purposes. The capital investment is divided into equal annual depreciation amounts. Salvage or residual values are not considered, since these were estimated to be less than 10% of the base costs (Herbst, 1980).

DEPRECIATION SCHEDULE FOR CAPITAL COST			
	Adjusted Cost 1997	Useful life (years)	Annual depreciation
Construction costs incl. design & supervision	$48,278	30	$1,609
Electrical system	$2,631	30	$88
Piping, weirs, and pumps	$3,181	10	$318
Totals:	$54,090		$2,015

Interests on the capital investment

The costs of financing the structure, the annual interest cost, have been based on the current (Nov. 1997) lending rates for mid-term agricultural loans. Such loans were negotiating at 7.25% for a 5-year term, and 8.25% for 10 years in November 1997. The 5-year term rate (7.25%) was selected because this is considered a short to mid-term investment.

Interests on investment = 1/2 capital cost X interest rate
Adjusted construction costs (1997) to finance: $54,090
Annual interest: $54,090/2 X 7.25% = $1,961

Annual operating costs

Annual operating costs comprise the electric consumption of the two pumps, a reasonable annual maintenance of the berms and grass cutting, the dredging of the first wetland marsh every decade and a major overhaul of the runoff distribution pipe work also every decade.

The total number of working hours for the two HP pumps has been estimated from the operation schedule (Weil, 1996):

Pump #1: 182 h/year X 13 Amps X 115 Volts/1000 = 272 kWh
Pump #2: 646 h/year X 13 Amps X 115 Volts/1000 = 966 kWh
Two pumps per year = 1238 kWh @ 0.06 $/kWh = 74 $/year

Every year, the small maintenance of the berms involving one farm average tractor and one operator demands 3 hours plus $100 supplies. Every year, two grass cuttings on the berms, on the filter strip and on the buffer zone demand 3 hours. Tractor costs set at 65$/hr.

6 hrs/year X 65 $/hr = $390/year + 100$ supplies

Total for routine yearly maintenance = 490 \$/year

Every 10 years, the design parameters call for the dredging of the first shallow wetland cell to maintain its original grade. This can be done without stopping the system, by dredging one-half of the surface, in strips across the flow direction, one year, doing the other half the next year. This way the well established cattails can easily recolonize the stripped area, without much loss in efficiency. A high hoe with long a reach can be positioned on the side berms and drag about 10 cm thick of sediments (along with cattails stems) from equally spaced strips. The dredged material could then be piled and left to dry up and compost for a while, awaiting to be spread onto land with the manure at a later time. Hourly rate for long reach high hoe for the work are estimated at \$150/hr. One dump truck at \$45/hr is also required for the same time. Time to perform the dredging (1353 m^2) is estimated at about 5 hours total for the whole cell.

High hoe: 5 hrs X 150 \$/hr = \$750
Dump truck: 5 hrs X 45 \$/hr = \$225
Total to dredge the shallow cell = \$975 every 10 years or 98 \$/year

Also every 10 years, about 10 hours work with a 60 H.P. farm tractor (plus one operator) to do small repairs on the berms. This includes time to replace the plastic distribution pipe for about \$100 of materials.

10 hrs X 65 \$/hr = \$650 + \$100 materials
Total for major maintenance = \$750 per 10 years or 75 \$/year

ANNUAL OPERATION AND MAINTENANCE	
Operations	Annual costs
Pumps	\$74
Routine maintenance and grass cutting	\$490
Dredging first shallow cell	\$98
Major maintenance every decade	\$75
Yearly total	\$737

Loss of land base

Dignard C.W. occupies 1.125 hectare (2.8 ac), including the berms, but excluding the wider than necessary central alley between the cells, that was customised to the producer’s needs. On that area of prime cropping land, the owner cannot grow profitable crops. An average crop loss based on typical crops for dairy operations in the region was used to estimated the loss revenues on the wetland area. The average gross margin per acre is evaluated at $181 per acre in 1997. For 2.8 ac, this represents $507 for loss revenues.

LOSS REVENUE ON THE CROPLAND OCCUPIED BY THE WETLAND					
Crop	Yield 1996[1]	Unit value[1]	Unit revenue[1] per acre	Operating expenses[2]	Gross margin per acre
grain corn	118 bu/ac	3.90 $/bu	460 $/ac	$241	$219
soybeans	42 bu/ac	10.02 $/bu	421 $/ac	$121	$300
barley	54.8 bu/ac	3.42 $/bu	187 $/ac	$119	$68
alfalfa hay	2.3 tons/ac	85.10 $/ton	196 $/ac	$58	$138
Sources: [1]OMAFRA 1997-1; [2]OMAFRA 1997-2			Average gross margin: $181/ac		

Total annual costs of the wetland system

All reasonable costs associated with owning, depreciating, financing have been converted on a yearly basis. The total annual costs is estimated at $5,220.

TOTAL ANNUAL COSTS of the Dignard Wetland	
Annual depreciation	$2,015
Interest on capital investment	$1,961
Operation and maintenance	$737
Loss of crop land	$507
Total annual costs - in 1997 $	$5,220

ALTERNATIVE FOR COST-BENEFIT COMPARISON

Without the present wetland system, the owner would have to resort to another solution acceptable to the environmental regulations. Currently, spreading the nutrient-laden runoff on crop land is the only other legal way of disposal. In the absence of the wetland to treat all the effluents, these would have to be stored in storage structures for a certain time, and periodically spread by a contractor. The owner would have to acquire expensive equipment and spend extended time which he does not have, if he were to do it by himself.

Runoff from the solid manure platform to which is added the milkhouse wastewaters, would be stored in the existing lagoon for a reasonable storage time. The runoff from the feedlot yard would have to be stored in a separate new lagoon to be properly sized, financed and constructed. Therefore, the wetland system actually includes the facultative pond (and its associated feed pump), where significant primary treatment is performed on the runoff waters. The spreading alternative would include the new lagoon and any improvements required on the existing one to make it conform to the minimum storage period.

Estimated volumes of runoff generated annually

The volume of wastewater has been estimated from the design parameters (Weil *et al*, 1994).

ESTIMATED ANNUAL RUNOFF VOLUMES TO BE SPREAD	
Manure runoff (from 1078 m^2 storage area/year)	334 m^3/year
Milkhouse wash water (tie stall, pipeline/ year)	517 m^3/year
Runoff from 0.75 ha exercise yard	2326 m^3/year
Net precipitation volume on existing lagoon	270 m^3/year
Net precipitation volume on exercise lagoon	198 m^3/year
TOTAL:	3645 m^3/year

Cost of spreading the annual runoff volumes

The total volume of runoff to be spread is 3645 m^3/year (802,000 gals/year). Typical rates charged by liquid manure haulers in Eastern Ontario in 1997 are $7 per 1000 gals for fields less than 2 km from lagoon. The rate climbs to $10 per 1000 gals for fields from 2 to 6 km (Pers.

Comm, Nov. 1997). Supposing that half the volume would be spread within 2 km of the lagoons, the annual costs of spreading the runoff is estimated as follows:

802,000 gals / 2 * $7/1000 gals = 2807 $/year
802,000 gals / 2 * $10/1000 gals = 4010 $/year
Total annual spreading costs: $2,807 + $4,010 = 6817 $/year

Cost of expanding/excavating lagoons

The existing earthen storage lagoon next to the manure platform has been expanded by 165 m^3. A new earthen storage lagoon (1334 m^3) will also have to be dug close to the feedlot yard to collect the runoff. Excavating costs for the earthen storage lagoons were estimated using the same rates as used during the construction of the wetland. A quotation was obtained from an experienced contractor. The expansion would demand no more than 5 hours of machinery time with a high hoe, while the new lagoon would require an estimated 50 hours of high hoe and a bulldozer (at $100/hr) to finish shaping the berms. The excavated materials would be spread around the new lagoon to berm it. It is customary for sizing calculations fees to be included in the machinery time. A 5' high chain link safety fence that include gates with latches is required around the lagoon (Hilborn, 1995), and current costs estimation have been obtained from a custom installer in Ottawa.

Machinery time: 55 hrs X 100 $/hr = $5500
Fence: $4400
Total: $9900

The annual depreciation would be based on 30 years like the wetland:
Annual depreciation: $9900 / 30 years = 330 $/year

The interest on capital costs is calculated using the same rate as for the wetland:
Interests on investment = 1/2 capital cost X interest rate
Lagoons construction costs to finance: $9900
Annual interest: $9900 / 2 X 7.25% = $359

ESTIMATED ANNUAL COST OF STORING AND SPREADING THE RUNOFF	
Annual spreading costs	$6,817
Annual depreciation on lagoon storage	$330
Average interests on capital investment	$359
TOTAL	$7,506

PARTIAL BUDGET

Results for this cost-benefits analysis can be summarised using a partial budget format, which is commonly used in farm management, to evaluate the financial implications of a proposed change on the profitability of the business. This particular format is adapted from Herbst (1980).

Proposed change: The situation is a dairy producer that has to spread large volumes of runoff waters by a custom operator. The alternative is to add a wetland to treat the contaminated runoff waters, saving on spreading costs. The runoff were stored in lagoons.

Modifications in manpower needs: No changes, since the work is performed by a contractor.

Modifications in the investments: The construction of the wetland is the major investment.

<table>
<tr><td colspan="2" align="center">PARTIAL BUDGET
Add an artificial wetland instead of custom spreading (on an annual basis)</td></tr>
<tr><td><u>Additional costs</u>: Wetland
a. Depreciated construction costs: $2015
b. Interests on investment: $1961
c. Operation and maintenance costs: <u>$737</u>
Total: $4713</td><td><u>Additional returns:</u></td></tr>
<tr><td><u>Reduced returns:</u>
e. Land area unusable for crops: $507</td><td><u>Reduced costs:</u> No more custom spreading
a. Spreading by tankers $6817
b. Construction of lagoons $330
c. Interests on investment: <u>$359</u>
Total: $7506</td></tr>
<tr><td>(A) Total annual additional costs and reduced returns:
$4713 + $507 = $5220</td><td>(B) Total annual additional returns and reduced costs:
$7506</td></tr>
<tr><td colspan="2">Net change in income (B minus A):$2286</td></tr>
<tr><td colspan="2">Notes: There is an improvement in income from the adoption of the wetland technology that is to replace the custom spreading of large volumes of runoff waters.</td></tr>
</table>

DISCUSSION

The total annual cost of owning, depreciating and operating the wetland system in 1997 Canadian dollars has been estimated at $5220, while the alternative of spreading the same runoff volume on land using a contractor would costs $7506. Thus, the alternative situation would be 44% more expensive. In other words, the construction of this wetland saves the farmer $2286 every year, or almost $70000 after 30 years of the useful life of the wetland.

The wetland pays for itself quite rapidly considering the costs of spreading and can be evaluated by the payback period for the investment in the wetland:

Payback period = total costs / annual cost of spreading
= $54,090 / $7,506/year = 7.2 years

Thus, the major investment required by constructing the wetland will be paid back shortly after the first 7 years of operation.

Ratios analysis

The costs of the wetland can be expressed as a function of chosen parameters like the size of the wetland, the size of the herd, or the volume of runoff water to be annually treated.

On a per-hectare basis: Total wetland investment / area of wetland (ha)
= $54,090 / 1.125 ha = $48,100 per hectare ($Cdn - 1997)

On a per-acre basis: Total wetland investment / area of wetland (ac)
= $54,090 / 2.78 ac = $19,500 per acre ($Cdn - 1997)

On a per-1000 gallons basis: Total wetland investment / total annual volume of runoff
= $54,090 / 802,000 gals = $67 per 1000 gals ($Cdn - 1997)

On a per-animal basis: Total wetland investment / number of animal units
= $54,090 / 190 a.u. = $285 per animal unit ($Cdn - 1997)

Non-financial returns

The existence of the wetland also brings benefits that are difficult to establish in financial terms, but are nonetheless important human aspects. Indeed, the owners enjoy an aquatic setting amidst their farmstead that draws many species of wildflowers and animals, including waterfowls. It also is being used as a relaxation place, where one can forget for a privileged moment the stressful necessities of managing a modern farm operation. One also does not have to coordinate the custom work operations into his crop management.

CONCLUSIONS

The choice of the wetland technology has been the best economical choice, because it allows the farmer to save a substantial amount of money over the alternative of spreading. And this is evident without considering other factors such as the quality of life brought by the aesthetic value of the wetland and the reduced stress of having to negotiate with manure haulers for timing of their operations and pricing.

SIMULATION OF COSTS FOR A MODIFIED WETLAND WITH WEEPING BEDS

More recent wetland systems are now built with shorter treatment cells, that allow a part of the nutrients to leave the wetland and be spread onto crop land. A design like this, with finishing irrigation pads, ensures the reduction of bacteria and allows the recycling of part of the nutrients that otherwise would be immobilised in the wetland cells. These finishing beds are usually planted to non-food crops or trees. They also act as buffers, preventing the accidental overflow of the wetland system during rainstorm events that may allow excessive nutrients and bacteria release into the environment.

One would require a complete design to estimate precisely their costs. However, it has been estimated that the modified wetland design would save about $5000 on the original construction costs of the Dignard wetland. The irrigation pipe work would require an additional investment, probably including a third pumping station, which may roughly costs a further $1000. Construction costs for the wetland would have been $4000 less, making it a smaller investment by 7%.

A smaller wetland system would have occupied a smaller land base. Supposing that the wetland is 20% smaller, it would allow a smaller loss in crop revenues of $100 per year (20% X $507). In addition, a part of the nutritional value of the runoff would be immediately returned to crop land, further improving the profitability of the wetland system.

It is apparent from the discussion, that the profitability of the wetland systems can be further improved by designing them smaller, allowing the final treatment of the runoff water by land irrigation.

REFERENCES

Collège d'Alfred. 1997. *Dignard Artificial Wetland*. Interim Report 1996: Year 2 of Operation, Draft. South Nation River Conservation Authority. Collège d'Alfred de l'Université de Guelph.

CRÉAQ. 1991. *Évaluation. Machinerie, bâtisses et équipement*. Le Comité de références économiques en agriculture du Québec. Agdex 824/825. Mars 1991.

Herbst, J.H. 1980 . *Farm Management: Principles, Budgets and Plans*. 5th Revised Edition. Stipes Publishing Co. Champaign, Ill. 288 pp.

Hilborn, Donald. 1995. *Storage of Liquid Manure*. OMAFRA Factsheet no. 94-097, Agdex 721.

OMAFRA (1). 1997. *Ontario Principal Field Crop Statistics; Area, Production and Farm Value, Ontario by County, 1996*. Internet document [url: http://www.gov.on.ca/OMAFRA/english/stats/crops]

OMAFRA (2). 1997. *Crop Budgets.* Publication 60.

OMAFRA. 1994. *Agricultural Pollution Control Manual*. Chap. Sizing Storages. Ontario Ministry of Agriculture, Food and Rural Affairs

Weil, Claude, William Kollaard, Ian Malcom and Olivier Fankhauser. 1997. *Constructed Wetlands for the Treatment of Farmstead Runoff in Eastern Ontario, Canada*. Paper presenter to the Fourth International Dairy Housing Conference, St. Louis, Mo. January 28-30, 1998.

Weil, Claude, William Kollaard, Ian Malcom and Leslie Vanclief. 1996. *Dignard Artificial Wetland: 1995 Year-end Report. A report on the construction and monitoring program 1994-1995.* South Nation River Conservation Authority, Collège d'Alfred, Ontario Ministry of Agriculture, Food and Rural Affairs.

Weil, Claude, William Kollaard and Éric Tousignant. 1994. *Design Report. Artificial Wetland - Dignard Farm, Embrun (On)*. Ontario Ministry of the Environment and Energy, Collège d'Alfred, Ontario Ministry of Agriculture, Food and Rural Affairs.

APPENDIX C

VILLAGE OF ALFRED DEMONSTRATION PROJECT

(CASE STUDY)

VILLAGE OF ALFRED DEMONSTRATION PROJECT
(by: Claude Weil, P.Eng, Olivier Fankhauser and Sarah Hurd, Alfred College)

Introduction

The Village of Alfred is located some 25 km west of the Town of Hawkesbury in Eastern Ontario. The Village is home to Alfred College of the University of Guelph and has a total population of approximately 1500 people. The Village's sanitary sewage is currently treated by a 2 cell sewage lagoon that discharge to the Azitica brook in the spring. The lagoon cells were constructed in the early 70's and have surpassed their design capacity. Furthermore the Azitica brook no longer has the assimilative capacity for the existing flows, yet alone any proposed increase. Due to these reasons, the Village engaged the Services of Stantec Consulting and Alfred College to undertake an environmental assessment study to look at alternative treatment systems. Part of the study includes looking at constructed wetland technology, combined with post wetland phosphorous treatment to allow for continuous summer discharge to the brook. The following is therefore a brief description of the pilot project that is currently underway to study the wetland and post wetland polishing alternative. The wetland system began operating in the summer of 1999 and will be monitored over the next few years.

Alfred Wetland

The pilot constructed wetland system has been designed to handle at least 5% of the flow entering the Alfred municipal lagoons, thus approximately 21,000 m^3 per year. The purpose of the project is to improve and test the design of a constructed wetland and to compare two methods of post-wetland polishing: vegetative filter strip and phosphorus adsorption filters.

The design of the constructed wetland is similar to the one Alfred College and McNeely Engineering (now Stantec Consulting) built in Embrun, Ontario in 1994. The Alfred Municipal wetland is a free-water surface three cell wetland system, composed of a wetland/pond/wetland. The wetlands are shallow basins (10-20 cm operating water depth) with densely growing vegetation. The pond is a 0.6 - 0.75 m deep pond wetland, without any vegetation.

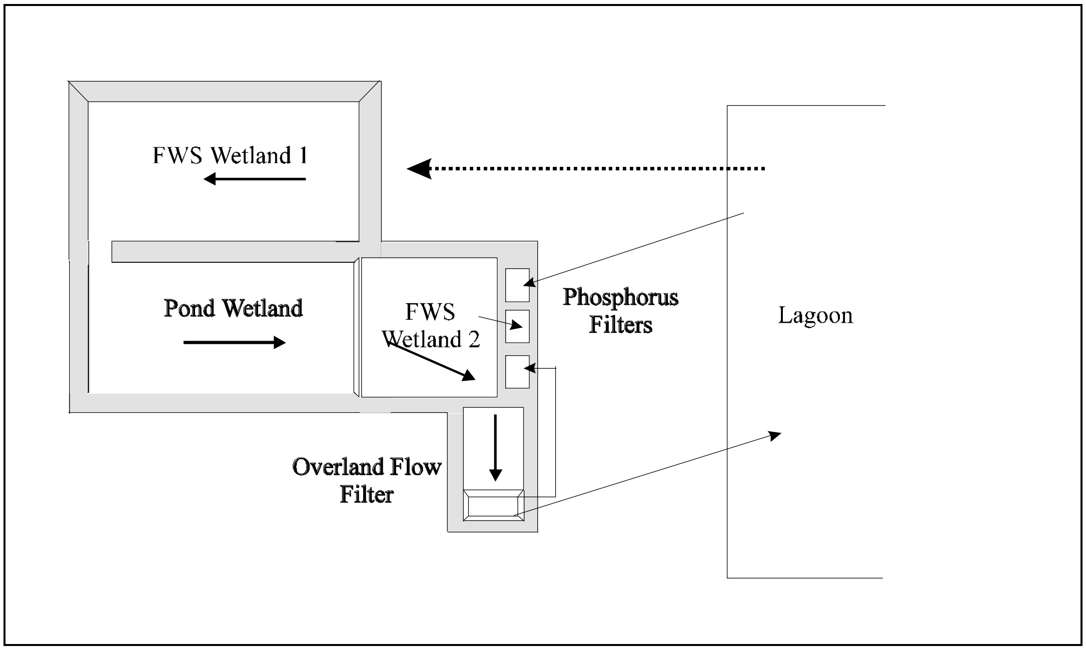
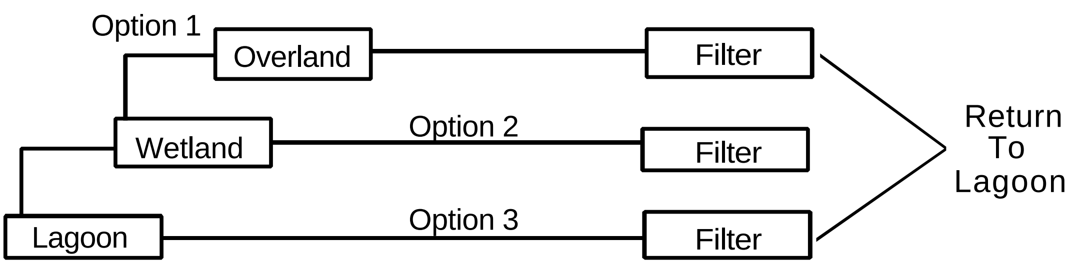


Figure 1: Components of the research/demonstration project

The wetland began operating during the summer of 1999.



Three scenarios as depicted in Figure 2 are currently being studied

Option 1) Wetland +Overland Flow + Adsorption Filters
Option 2) Wetland +Adsorption Filters
Option 3) Adsorption Filters

All the treated wastewater is returned to the lagoons during the research work. There is no direct discharge to a stream.

The design of the Alfred wetland is based on the following assumptions:

1. the constructed wetland treats the lagoon effluent from May 15th to September 28th (136 days)
2. the wetland is designed to treat 5% of the lagoon effluent, thus approximately 21,444 m^3/yr.

3. design criteria are the following: BOD_5 loading rate of 100 kg/ha/day, nitrogen loading rate of 3 kg/ha/day and a retention time of approximately 15 days. This gave the following results.

21,444 m^3 treated from May 15th to September 28th	= 136 days
treatment flow	= 158 m^3/day
required area with a BOD_5 influent of 15mg/L	= 237 m^2 (0.02 ha)
required area with a nitrogen influent of 20 mg/L	= 10,512 m^2 (1.05 ha)
required area for a retention time of 15 days	= 7,884 m^2 (0.79 ha)

The above loading rates were used to determine a preliminary size for the constructed wetland. A more precise required area was determined using plug-flow kinetics.

Kadlec and Knight (1996) analyzed the data from the North American Treatment System Database (NADB), a system developed to provide a quantitative basis for the planning and designing new systems. Based on this analysis, parameter values were developed for the plug flow model (BOD5, TSS, N-NH4, TN, TP and Faecal Coliforms). The model was calibrated for the influent and effluent concentrations indicated in Table 1 and the areal rate constants were computed for an average summer temperature of 17.6 °C. Total nitrogen was estimated to be roughly equal to TKN (there are limited amounts of nitrates and nitrites compared to TKN). The resulting area is 0.75 ha and is based on the area requirement to satisfy total nitrogen criteria.

Table 1: Area calculations based on the plug-flow model and NADB data

	TSS	**BOD**	**TP**	**TN**	**Norg**	**N-NH_4**	**FC**
Influent (mg/l)	80	15	1	20	15	5	100000
Target effluent (mg/l)	18	5	0.5	6	3.5	1.5	350
Wetland background (mg/l)	17.7	4.3	0	1.5	1.5	0	300
Areal rate constant (m/yr)	1000	34	12	11	15	16	75
Required area (ha)	0	0.45	0.34	**0.75**	0.72	0.42	0.57

Note: FC=Fecal Coliforms (concentration in 100 per ml).

Hammer's criteria of 3kg TKN/ha/day is too restrictive and was based on conservative assumptions due to a lack of data at the time. For example, the marsh/pond/marsh component of the Embrun treatment system had a load of approximately 4.8kg/ha/day and reduced TKN concentration by an average 74% during its two years of operation. Also, the average constructed wetland in the NADB has a loading of 7.6 kg/ha/day. Based on this information, a conservative wetland area of 0.78ha is chosen.

During the 1996 and 1997 monitoring seasons of the Embrun wetland, the average pollutant concentration reduction in the marsh/pond/marsh components of the wetland were 79% for BOD_5, 74% for TKN and 65% for TP with loadings of approximately 9.9, 4.8 and 0.8kg/ha/day, respectively. The proposed Alfred constructed wetland loads would be 2.9, 3.9 and 0.2, respectively. Based on the performance of the constructed wetland in Embrun and considering the fact that the loads are lower in Alfred, the effluent should have concentrations lower than 0.35mg/l for phosphorus, 5.2mg/l for TKN and 3.2mg/l for BOD_5 prior to any polishing step.

However, the concentrations of pollutants that were encountered in Embrun were higher, and it is known that the performance of constructed wetlands is diminished with lower pollutant concentrations. Therefore, it is important to look at the literature to better assess the performance that should be expected.

Pollutants removal of constructed wetlands is better understood for high pollutant concentrations. In particular, the effluent coming out of a wetland cannot have lower concentrations than natural background levels. For example, natural wetlands have BOD_5 and total nitrogen concentrations of 1-6mg/l and 1-2mg/l, respectively. Kadlec & Knight (1996) have developed inlet-outlet concentration regression equations and parameter values for the plug flow model based on data of approximately 50 surface flow constructed wetland. The resulting concentrations for a 0.79ha constructed wetland under our climatic conditions are indicated in Table 2.

Table 2: Expected performance of a 0.79ha wetland according to Kadlec & Knight

	TSS	**BOD**	**TP**	**TN**	**Norg**	**N-NH_4**	**FC**
Influent (mg/l)	80	15	1	20	15	5	100000
Plug-flow model (mg/l)	17.7	4.4	0.22	6	3.3	0.6	305
Regression equations (mg/l)	17.7	7.3	0.29	8.4	N/A	1.5	500

The expected performance based on the data from the Embrun constructed wetland is in the same range as the one predicted from the regression equations and the plug flow model. Combining the information, the expected performance is presented in Table 3. Performance might be higher than expected for TKN and BOD_5 and, as a result, loads might be increased during the experiment. Phosphorus removal by natural systems can fluctuate substantially over the short (i.e. release of adsorbed phosphorus) and long-term (i.e. all adsorption sites are full). For this reason, it has to be considered that the constructed wetland might have little or no effect on phosphorus concentration after a few years. For this reason, other components have been added to the treatment system to remove phosphorus.

Table 3: Expected performance of the constructed wetland

	Total nitrogen	**Phosphorus**	**BOD_5**
Lagoon effluent	20mg/l	1mg/l	15mg/l
Constructed Wetland	5-8mg/l	0.2-0.4mg/l	3-7mg/l

Compartmentalization

The configuration of the pilot constructed wetland is similar to the Embrun constructed wetland with some improvements. For this reason, it is composed of a marsh, followed by an aerobic pond and a final marsh. However, the size of the first cell has been increased because the load on this component was too high in Embrun compared to the other parts of the system. To have a loading of approximately 10kg TKN/ha/day on the first cell, the distribution of the areas of the marsh/pond/marsh have been set at 2:2:1. This results in areas for the three components of approximately 0.31, 0.31 and 0.16ha, respectively. To respect a length to width ratio of 1:1-5:1, the width has been set to 40m at operating depth for all components. The dimensions of the components are summarized in Table 4.

Table 4: *Dimensions of the constructed wetland components at operating depth*

	Marsh 1	Aerobic pond	Marsh 2
Area (ha)	0.31	0.31	0.16
Width (m)	78	78	40
Length (m)	40	40	39
Operating depth (m)	0.15	0.6	0.15

Berms

All the precipitation during the non-operating period (October 1-May 15) will be stored in the system. To allow for a contingency and flexibility, this storage period is extended by 15 days at the beginning and the end of the operating season. The net precipitation from September 16 to May 31 was computed for the constructed wetland in Embrun based on an analysis of the climatic data of the Ottawa International Airport. Its value was 379mm for an average year and 523mm for a 10-yr wet winter. The net precipitations for a 10-yr wet summer (May 15-September 30), 10-yr wet summer month (September) and for a 24h storm with a 25 years return period are much lower (9.85mm, 59mm and 84.5mm, respectively). For this reason the value of 523mm above operating depth is retained for design purpose.

According to Kadlec & Knight (1996), approximately 10mm/yr should be taken into account for the lifetime loss of freeboard due to sediment and plant accumulation. As this pilot constructed wetland might be kept for demonstration purposes, the lifetime was set at 20 years. Thus, the spillway is located 87cm above the bottom level of the wetland cells (operating depth + sediment accumulation + winter storage = 15cm + 20cm + 52cm). The top of the berm is set at an additional 13cm above the spillway, thus at a height of 1 metre above the bottom of the wetland cells.

The berms are designed to allow for easy maintenance of the system (i.e. cutting the grass). The side slope is 3:1. The width of the berms at operational depth is larger than 5 metres to avoid penetration by muskrats. The core of the berm is composed of reworked compacted clay.

Additional information

- The constructed wetland inlet is designed to increase aeration of the lagoon effluent. It is composed of a 100mm PVC gated pipe at the top of the berm. The wastewater is aerated as it cascades down a rip-rap slope.
- Final grading tolerance is set at ± 3cm to maintain sheet flow conditions in the wetland cells.
- Interior berms (35cm high, 50cm width) composed of topsoil are constructed in the wetland cells to improve water distribution and prevent channelisation. A deeper area at the outlet of the second wetland is also be built for this purpose.

- Water levels are controlled with a stop-log weir (adjustable) and/or a pivoting outlet pipe. A large screen must be placed in front of the outlet structure to prevent clogging.

Overland Flow Filter

- Part of the effluent (39m^3/day) of the constructed wetland is treated with an overland flow system. Its design is based on parameters found in Metcalf & Eddy (1991):

  Application rate = 4-10 l/min/m slope width
  Slope length = 30-45 metres
  Application period/Dry period = 0.5-1
  Slope = 1-8%

- In order to remove up to 90% of BOD_5, 70% of nitrogen and 50% of phosphorus, the design is based on the following:

  Application rate = 4 l/min/m slope width
  Slope length = 30 metres
  Application period/Dry period = 0.5 (8 hours per day)

This results in a flow of 4.8 m^3/h and an area requirement of 600m^2 (20m width). With the area required for the berms and a collection storage, the total area is 900m^2. The overland flow system is composed of compacted clay overlaid with at least 30cm of topsoil. The wastewater is distributed using a 100mm PVC gated pipe. Overland flow increases the aeration of the effluent, which is beneficial for phosphorus removal in the last stage of treatment. This process is also expected to kill pathogens (effect of sunlight). A storage collects the effluent before further treatment and act as a buffer against storms.

The system performance will be monitored over the next few years (Table 5) and will have to be verified with the research/demonstration unit, as it is difficult to predict performance at such low concentrations. Harvesting the hay will aid in the removal of phosphorus at a rate of 50-90 kg P_2O_5/ha/year. Assuming that the average influent has a concentration of 0.45mg/l, this would mean that the P_2O_5 load would be 90 kg/ha/year. Therefore, almost all of the phosphorus applied could be removed by vegetal uptake and hay harvesting. Loading will be increased or lowered based on the performance with the design loading of 4 l/min/m of slope width.

Table 5: Expected performance of the constructed wetland/overland flow system

	Total nitrogen	**Phosphorus**	**BOD_5**
Lagoon effluent	20mg/l	1mg/l	15mg/l
Constructed Wetland	5-7mg/l	0.4-0.5mg/l	5-8mg/l
Overland flow	<3mg/l	<0.3mg/l	<3mg/l

Phosphorus removal stage

It may be necessary to have a last stage of treatment for phosphorus removal to achieve low constant concentrations in the system effluent. This could allow for future summer long direct discharge into a ditch if effluent concentrations of less than 0.1 mg/l are sustained. Phosphorus removal by natural systems can fluctuate substantially over the short and long-term. Phosphorus removal can be achieved using a filter composed of adsorbing media (i.e. clay pellets, peat, blast furnaces slag, steel furnace slag, sand). For example, blast furnace slag can remove up to 44g of phosphorus per kg of media (Sakadevan & Bavor, 1998). This capacity to remove phosphorus is essentially due to its content in aluminum, iron and calcium. Testing of different types of materials will be carried out in the laboratory and the most promising media will be selected for field experiment.

The final design of the filter and the set-up of the demonstration site are dependent on the characteristics of the selected media (hydraulic conductivity, contact time and porosity). Three filters have been installed on site to treat the effluents from the lagoon, the constructed wetland and the overland flow. Three loading modes may be used: horizontal flow, vertical upflow and vertical downflow. A pre-treatment with a roughing filter (coarser material) might be necessary to reduce clogging.

Filter volumes for a given contact time are similar for both horizontal flow and vertical downflow filters. The choice between vertical and horizontal flow filters will therefore be dependent on the operational and capital costs. For example, it is easier to remove the media in horizontal flow filters, but easier to unclog vertical flow filters. Horizontal flow filters can be vegetated. This allows the transport of oxygen to the media and thus favours phosphorus adsorption. Vertical flow filters can be oxygenated by either bringing the water in pulses or by installing an aeration system in the filter. Finally, horizontal flow filters have less mechanical components. Andersson et al. (1992) mention that there is very limited experience in using vertical upflow filters in large-scale operations. According to these authors, wastewater treatment with upflow filters does not seem to yield better performance than downflow filters. Finally, energy requirements and capital costs are much higher for upflow filters.

The above information has been taken into consideration in deciding if vertical or horizontal flow filters should be used, yet it seems that slow-rate downflow filters would be more appropriate to remove phosphorus from municipal wastewater. The flow could be applied intermittently to allow for decay of organic matter and in order to increase phosphorus removal (aeration), as it is the case for the New Hamburg process (Evans et al., 1994; Melcer et al., 1995). The possibility to directly treat the lagoon effluent with the filter and its performance in removing phosphorus, BOD_5 and nitrogen will be evaluated in this demonstration project. Finally, the possible contamination of the effluent with heavy metals will be assessed.

Blast Furnace Slag (BFS), which was mentioned above for its high adsorption capacity, has the appearance of coarse sand (Sakadevan & Bavor, 1998). This means that its hydraulic conductivity is approximately 10^{-2} B 10^{-3} m/s and its porosity is between 20-50% (Holtz et al., 1991). The calculations for the vertical downflow filter are based on recommendations for slow sand filters. These filters do not only retain suspended solids, but also have a long enough contact time to allow for biological reactions and adsorption processes. Based on a design flow of $2.4m^3/h$ and according to the recommendation of a daily loading of $0.1\text{-}0.2m^3/m^2$/hour for slow-rate sand filters (Vigneswaran & Visvanathan, 1995; Hendricks, 1991; Collins & Graham, 1994; Maystre & Krayenbuhl, 1994), the required area is between 12 and 24 m^2.

This loading rate is similar to the instant loading rate used in the New Hamburg process ($0.13m^3/m^2/h$), an intermittent sand filter used to treat municipal lagoon effluent (Evans et al., 1994; Melcer et al., 1995). Therefore, the effluent could be applied during the night to prevent algae growth and dry during the day. Continuous and intermittent loading will be tested with the pilot system in the field. Based on this loading, the contact time for a filter with a depth of 0.7m would be almost two hours, which is acceptable. This provides a theoretical lifetime of 80 years assuming an adsorption capacity of 57kg P per m^3 for BFS and a continuous loading. It might be possible to further reduce the area if shorter contact times provide an acceptable effluent.

Conclusion

This pilot project will establish if a full-scale treatment system composed of a constructed wetland to treat the municipal lagoon effluent of the municipality of Alfred is feasible as the most economical option. The impact of the pilot system on the environment should be minimal, as all the treated wastewater is returned to the lagoons.

References

Andersson, C., M. Tendaj and M. Rothman. 1992. Filtration at Bromma sewage treatment plant. *Water Science and Technology* 25: 59-66.

Collins, M.R. and M.J.D. Graham. 1994. Slow sand filtration: an international compilation of recent scientific and operational developments. American Water Works Association, Denver, Colorado.

Evans, B., S. Nutt, T.Ho and H. Melcer. 1994. Alternative approaches for upgrading effluent quality for lagoon based systems. *Water Science and Technology* 10: 201-205.

Hendricks, D. 1991. Manual of design of slow sand filtration. AWWA Research Foundation, Denver, Colorado.

Kadlec, R.H. and R.L. Knight. 1996. Treatment wetlands. CRC Press LLC, Boca Raton, Florida.

Maystre, L.Y. and L. Krayenbuhl. 1994. Approvisionnement en eau potable. DGR-IGE, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland.

Melcer, H., B. Evans, S.G. Nutt and A.Ho. 1995. Upgrading effluent quality for lagoon-based systems. *Water Science and Technology* 12:379-387.

Nutt, S.G. 1991. A review of approaches to achieve low effluent phosphorus concentrations. *Water Pollution Research Journal of Canada* 26:495-547.

Sakadevan, K. and H.J. Bavor. 1998. Phosphate adsorption characteristics of soils, slags and zeolite to be used as substrates in constructed wetland systems. *Water Resources* 32:393-399.

APPENDIX D

Swine Manure Treatment

Strategies to Reduce Hauling and Disposal Costs

Swine Manure Treatment - Strategies to Reduce Hauling and Disposal Costs
(by: Olivier Fanhauser, Alfred College)

INTRODUCTION

Expanding Asian and domestic markets have created opportunities for Canadian pork producers to expand their operations and have allowed new producers to enter the market. By extension, new opportunities have opened up for manufacturers, contractors and consultants who can facilitate expansion or the establishment of swine operations. The availability of land for spreading manure often limits expansion in areas of intensive livestock production of North America and Europe. Despite the fact that a number of manure "treatment" technologies have been tested and have shown great potential, there is no technology commercially available to most producers that would limit their land base requirements for spreading manure. Reasons for this lack of technology transfer may include high capital costs of installing wastewater treatment equipment and lack of trained personnel for operating the system.

Three potential strategies for overcoming these obstacles are discussed in this report:
1) hauling excess liquid swine manure to a central wastewater treatment plant;
2) constructing low maintenance, affordable on-farm treatment systems; and
3) treating swine manure in mobile treatment units operated in batches by a trained custom operator.

The section on central treatment plants is a brief summary of the European experience, as covered in more detail in the publication "Situation du Traitement du Lisier dans le Monde". In the next two sections, candidate technologies for on-farm and mobile treatment systems are identified.

The report also includes the results of preliminary laboratory work on chemical pre-treatment. The goal of pretreatment is to lower the suspended solids and/or nutrient loading into the next "downstream" component of the treatment system. Since chemical precipitation generally requires relatively short reaction times (compared to biological processes) and can be achieved as a batch process, it was identified as a good candidate technology for pre-treatment in either a portable reactor or in an existing manure tank.

CENTRAL TREATMENT PLANTS

Central treatment plants have been considered as an alternative to construction separate plants on each swine operation. Central plants offer the advantage of spreading capital and operating costs among several users. Furthermore, the plants can be operated by trained wastewater treatment technicians and can therefore make use of more complex technologies. However, a central treatment plant presents several key disadvantages:

- often requires high capital costs and high financial risk;
- requires transport of manure to treatment plant;

- creates a potential siting problem ("not in my backyard") and target for protest groups;
- as in the case of other large projects, such as incinerators, may require transport of manure from distant regions to be viable;
- potential to become "white elephant" if surrounding farms change production in the future.

A number of central treatment plants have been proposed in Europe. These were recently reviewed . A brief account of some of these systems is presented below.

In the late 1980's, a central treatment plant called PROMEST, with a capacity of 500 000 tonnes per year, was constructed in the Netherlands. The system involved anaerobic digestion, aerobic digestion and solid-liquid separation with subsequent evaporation of the liquid phase and drying of sludge. The plant could not compete with long distance hauling and spreading of manure and was abandoned because it was not economically viable. The Dutch also developed a process known as VAN ASPERT, which involves filtration, acidification then evaporation, subsequent condensation of the vapour and finally reverse osmosis of the condensate. The process did not seem financially viable and was not pursued commercially.

In Denmark, eighteen collective biogas plants were constructed to treat a mixture of swine manure, cattle manure and organic food industry byproducts. Biogas is used to heat houses and to produce electricity. A concentrated, low-odour, pathogen-free fertilizer is also produced by the process.

In France, much of the research and development work has been focussed on nitrification-denitrification systems (among these are AGROCLAR, DENITRAL, VAL-EPURE, TECHNOLYSE and TERNOIS). The goal of these systems is to convert organic nitrogen and ammonia-nitrogen into harmless nitrogen gas, N_2, the major component of our atmosphere. It may be argued that this strategy is wasteful - a useful "natural" nutrient source is volatilized while commercial inorganic sources of nitrogen continue to be spread as fertilizers. Although some academics may present a moral argument against such practices, it is likely that many producers would happily "waste" manure nitrogen in favour of buying a consistent nitrogen-phosphorus-potassium mixture (which is more easily spread, has a less offensive odour and provides a more consistent fertilizing value since there is no question over the availability of the nitrogen to the crop).

Other French technologies (SIRVEN, AMOLIS PHYSICO and SMELOX-IFP) strip ammonia-nitrogen (i.e. convert dissolved ammonium, NH_4^+, into gaseous ammonia, NH_3) and either recapture the volatilized ammonia in an acidic solution or burn it at high temperatures. A third strategy tested by the French is chemical precipitation of ammonium. A process called "AVDA" has been proposed, in which phosphoric acid and magnesium oxide are used to precipitate ammonia-nitrogen. The recovered sludge may be a valuable fertilizer.

Precipitation of magnesium ammonium phosphate was also considered for central treatment in Germany (where it was called the MAP process and tested at the pilot plant level). This type of treatment may also be applicable to either individual on-farm treatment systems or to a mobile batch treatment system. (It was therefore decided to carry out preliminary laboratory tests on magnesium ammonium phosphate precipitation-the results at the end of this report.)

Another more complex German central treatment plant, named SULZER, was installed in a region deemed to be environmentally sensitive. The SULZER system involved physical solid/liquid separation, anaerobic digestion with biogas production, precipitation with lime, ammonia stripping, ammonia recovery in an acid solution and aerobic treatment. Despite the complexity of the treatment system, the final effluent did not meet effluent discharge criteria and had to be spread on agricultural land.

Four other pilot central treatment plants have been installed in Germany since 1990 for treating swine manure mixed with cattle manure or food processing wastes. The FINSTERWALDE system in an anaerobic digester with biogas production to generate heat and electricity. Following digestion, solids are mechanically separated from the liquids. The solids are composted and the liquid fraction is stripped of ammonia. The ammonia is then crystallized as NH_4HCO_3.

In the LINGEN system, the solid and liquid fractions are separated mechanically. The liquid fraction is then evaporated to produce a concentrate and the solids are composted. Ammonia gas is trapped in an acid solution, which is treated anaerobically and aerobically prior to discharge to a surface water. The LINGEN system was over-sized and operates only at about 13% of capacity.

The PFAFFENDORF system involves: mechanical separation of liquids and solids; anaerobic treatment of liquids; composting of solids; ammonia stripping; nitrification-denitrification; and lime addition. The PFAFFENDORF system was also over-sized and operates at about 62% of its capacity.

In the SURWOLD system, the manure is treated anaerobically, separated mechanically, acidified and run through a reverse osmosis unit.

The complexity of the European central treatment plants illustrates the technical challenges associated with swine manure treatment as well as the severity of the problem of excessive manure production in certain regions of the continent. Considering the problems associated with a number of these systems using different technologies, the overall strategy of shipping manure to a central treatment plant is questionable. Most of the technologies considered would likely be too expensive and too complicated to be incorporated into on-farm treatment systems.

ON-FARM TREATMENT SYSTEMS

On-farm manure treatment eliminates the need to transport large volumes off-site. However, on-farm systems require an original capital investment, some operator attention and the use of some land.

I Composting

Manure composting systems usually concentrate on maximizing the value of the compost, so that a more valuable end product is produced. However, Agriculture Canada researchers have introduced an intelligent new strategy for composting: separate the solid and liquid fractions by gravity, compost the solids with the straw bedding material as a bulking agent, use the heat of the compost pile to evaporate the liquid fraction. Once the composting process is well established, mixed liquid manure can be continuously fed into the pile. This strategy reduces the volume of liquid which must be transported off-site. Trials have been successfully completed in Ottawa, Ontario by Dr. Naveen Patni and in Agassiz, B.C. by Dr. John Paul, the latter using broiler litter as a bulking agent to start up the composting process (personal communications, June 1997). Composting requires a certain degree of operator attention but little technical expertise (if proper operating guidelines are established).

Compost has a high adsorption capacity and is therefore effective in reducing odours and trapping ammonia. Dr. Patni conducted composting trials using passive aeration in 1996, and prepared a final report at the end of 1997.

The approach of using the heat of the compost to evaporate the liquid fraction of swine manure will be followed by Dr. James Morris and Ronald Fleming of Ridgetown Agricultural College, University of Guelph. In the Ridgetown compost trials, forced aeration will be employed so that a higher rate of evaporation is expected. The cost of the experimental composting structure is approximately $70 000. However, the cost of an on-farm system is expected to be much lower.

The idea seems to have great potential as a simple method of reducing transportation costs, and retaining much of the nutrient value of the manure.

II Wetlands

Although wetlands can be used as stand alone treatment systems for weaker agricultural wastewaters such as runoff, it is generally accepted that pre-treatment is required if wetlands are to be used for liquid livestock manure. Anaerobic lagoons and facultative stabilization ponds are often used to remove the bulk of the organic matter and nutrients, with wetlands provided for final polishing. Final disposal of manure treated by a lagoon/wetland combination is normally achieved via land spreading.

The design size of constructed wetlands for livestock manure treatment is usually based on allowable surface loading rates of either nitrogen (TKN or NH_3 + NH_4-N) or biochemical oxygen demand (BOD_5).

Estimated Mass Pollutant Loads in Storage Units

The BOD_5 production from manure from hogs between 45 kg and 136 kg (100 to 300 lbs) has been estimated as 0.32 kg/hog/day. Using the Ontario Ministry of Agriculture and Food's estimate of 10.2 L of liquid manure produced per hog per day, BOD_5 concentration can be estimated to be 31 000 mg/L for swine excreta with measurements taken in Ontario (according to Dr. Naveen Patni and Mr. Ronald Fleming, personal communications June 1997). It is estimated that a 500 animal farrowing and finishing operation would produce only 90 kg BOD_5/day, which is equivalent to 0.18 kg BOD_5/day. This estimate is equivalent to the BOD_5 production of hogs between 9 and 41 kg.

The Ontario Ministry of Agriculture, Food and Rural Affairs' (OMAFRA) nutrient management planning software assumes a TKN concentration of 3700 mg/L (2300 mg/L NH_3-N and 1400 mg/L organic-N) in liquid swine manure tanks or lagoons. This value is based on extensive testing of slurry in manure tanks in Ontario and is consistent with the concentration of 3000 mg/L reported. Using the OMAFRA's estimated manure production of 10.2 L/hog/day (0.36 ft^3/hog/day for pigs between 130 and 170 lbs, including wash water and spillage), the mass load of TKN can be estimated to be 37.7 x 10^{-3} kg TKN/hog/day.

Estimated mass load/hog (produced year round in manure tank or storage lagoon):

BOD_5: 0.32 kg/hog/day

TKN: 0.038 kg/hog/day

<u>Note:</u> Since the BOD_5 and TKN loads of 0.32 kgBOD_5/hog/day and 0.038 kg TKN/hog/day were calculated based on concentrations recorded for slurry samples taken within manure tanks, they may be assumed for losses. Therefore, no additional reduction in concentrations were assumed in the storage units. As discussed below, it is possible that BOD levels in the supernatant of the storage unit may be lower than estimated, if the tank is not agitated and the liquid fraction is decanted.

Pre-treatment in Anaerobic Lagoons

An anaerobic lagoon can be expected to lower the BOD_5 loading of livestock manure by 40 to 60% at temperatures between 20 and 25^{o}C (which would be representative of summer conditions in Ontario) over a retention time of only 5 days with a loading rate of 0.3 kg BOD_5/m^3/day. Ttwo swine manure lagoons, connected in series, with a combined removal of 60% BOD_5 in design calculations for sizing a wetland for final polishing of the effluent.

TKN is removed by sedimentation of solids (including biomass) and volatilization of nitrogenous gases such as ammonia (there is little conversion into nitrate because of the lack of oxygen). Iowa State University estimates nitrogen losses in anaerobic lagoons treating livestock manure to be between 60 and 70% (at Iowa State University in 1995).

If an additional anaerobic lagoon, following the storage unit, were to be put into operation for approximately 4 months a year as a pre-treatment step for a constructed wetland, its influent loading rates would be three times discharged by the manure tank: 0.96 kg BOD_5/hog/day and 0.11 kg TKN/hog/day. Using a volumetric loading rate of 0.3 kg BOD_5/m^3/day, the design volume of an anaerobic lagoon would be 3.2 m^3/hog. Assuming 50% BOD_5 removal and 60% TKN removal, the mass pollutant load discharged by the lagoon would be 0.48 kg BOD_5/hog/day and 0.044 kg TKN/hog/day.

Size of anaerobic lagoon

3.2 m^3/hog or 3200 m^3 per 1000 grower/finishing hogs

Expected load discharged by lagoon (operated 4 months)

0.48 kg BOD_5/hog/day

0.044 kg TKN/hog/day

It should be noted that there exist a great discrepancy in the removal rates reported above and concentrations reported for swine manure lagoons in other references. In Iowa, Montana, Indiana and Alabama, data was examined from the analysis of samples collected over a four year period from the supernatant of five swine manure lagoons (used for recycling in flush systems with high water use). It was found that average COD values ranged between 970 mg/L and 2371 mg/L. Since the ratio of COD: BOD_5 for swine manure has been reported as approximately 3:1, the BOD_5 would be approximately 300 mg/L to 800 mg/L. These values are a factor of 100 lower than the estimate used in this report for stored swine manure. Part of the discrepancy is undoubtedly due to dilution. However, the TKN concentrations for these five lagoons were reported as averaging between 391 mg/L and 827 mg/L, only a factor of ten lower than the value of 3700 mg/L used in this report. Similar values have been reported: a BOD_5 concentration of 287 mg/L and a TKN concentration of 365 mg/L in an anaerobic lagoon loaded with swine manure. That effluent from a series of two lagoons treating swine manure diluted with fresh pond water had an average BOD_5 concentration of 63.7 mg/L and a TKN concentration of 69.8 mg/L.

In each of these cases, the influent BOD_5 loading to these lagoons should have been approximately ten times the TKN loading. If removal rates for both parameters had been similar, the BOD_5 concentration should have remained ten times higher than the TKN following treatment and dilution in the lagoon. The fact that lagoon samples had BOD_5

concentrations almost equal to TKN concentrations (sometimes BOD was even lower than TKN) suggests that the BOD removal rate of up to 60% in anaerobic lagoons treating swine manure may be extremely conservative. This may be due to the fact that solids tend to settle out of swine manure more readily that in the case with cattle manure. Sedimentation would be expected to remove BOD associated with particular matter but would have less of an effect on nitrogen (most of which would be dissolved).

Treatment in Facultative Ponds

At the Dignard Constructed Wetland, designed by McNeely Engineering (now Stantec Consulting) and Alfred College to treat exercise yard runoff and leachate from a solid manure pile, a facultative pond is used in combination with an anaerobic lagoon for pre-treatment "upstream" of the wetland system. The pond receives wastewater from the anaerobic lagoon at surface loading rates of approximately 128 kg BOD_5/ha/day and 44 kg TKN/ha/day. It achieves approximately 91% BOD_5 and 88% TKN removal (it is not operated during the winter).

Applying a design loading rate of 130 kg BOD_5/ha/day, a facultative pond for treating grower/finishing swine manure effluent from an anaerobic lagoon should be sized at 3.6 $x10^{-3}$ ha/hog. A facultative pond for 1000 pigs would be 3.6 ha. This is unrealistic. Since a higher loading rate may result in anaerobic conditions developing in the pond, it would be necessary to aerate in order to reduce the surface area and maintain an aerobic zone in the pond.

Assuming aeration is provided, it is estimated that a facultative pond would remove approximately 80% BOD_5 and 70% TKN from swine manure previously stored in a tank or anaerobic lagoon. The pollutant load discharged by the facultative pond would therefore be approximately: 0.096 kg BOD_5/hog/day and 0.013 kg TKN/hog/day.

Surface area of facultative pond: Prohibitively large, aeration should be provided to reduce area

3.6 X 10^{-3} ha/hog or 3.6 ha/100 grower/finishing hogs

Estimated load discharged by facultative pond:

0.096 kg BOD_5/hog/day

0.013 kg TKN/hog/day.

Sizing a Wetland Using Design Loading Rates

The design BOD_5 and TKN surface loading into pond/marsh/pond-type wetlands has been establishing as 70 kg BOD_5/ha/day and 3 kg TKN/ha/day for high quality effluent.

Using these design criteria and the expected mass loading of 0.096 kg BOD_5/hog/day and 0.013 kg TKN/hog/day for pre-treated swine manure, the total size of the pond/marsh/pond-type wetlands would be 1.3×10^{-3} ha/hog, based on BOD projections, and 4.3×10^{-3} ha/hog based on TKN projections for swine finishing operations. The limiting factor in the design of the wetland would therefore be the TKN concentration of the swine manure. Based on these projections, a growing/finishing operation with 1000 hogs would require a wetland system with a land base of 4.3 ha, which is excessive. However, the nitrogen removal efficiency achieved with wetlands using this design (the Dignard system discharges only 20 mg/L of TKN onto a vegetative filter at its outlet) is not necessary if its effluent is to be spread on agricultural fields. The highest TKN loading which could be applied (before BOD were to become the limiting factor) would 10 kg N/ha/day.

It has been reported that over 95% N removal can be achieved with a surface loading rate of 14 kg N/ha/day. Other studies have reported 71% N removal at a loading rate of 14.3 kg N/ha/day and 89% removal at 11.5 kg N/ha/day. In another study, the loading rate for an experimental wetland system treating swine manure was increased from 3 kg N/ha/day to 10 kg N/ha/day, since its effluent was to be disposed via terminal land application and therefore did not require the high level of treatment achieved at the lower loading rate (at which >90% TKN removal and 73% TP removal were reported). (It should be noted that in each of these studies, the BOD_5 load was lower than projected in this report, and was not the limiting design factor.)

Following the design calculations made previously, a loading rate of 10 kg N/ha/day would be used, the required area of the wetland treatment system would be 1.3×10^{-3} ha/hog (BOD would be limiting design factor). If the system performance were be comparable to that of similar wetlands and 85% mass removal of nitrogen is assumed, the mass load in the wetland effluent would be approximately 2.0×10^{-3} kg N/hog/day.

Design wetland surface loading rates:

TKN: 10 kg/ha/day
BOD_5: 70 kg BOD_5/ha/day

Design size of wetland:

1.3×10^{-3} ha/hog (1.3 ha per 1000 grower/finishing hogs)

Expected effluent nitrogen load:

2.0×10^{-3} kg N/hog/day

Terminal Land Application

The effluent from the wetland could be collected in a pond and spread or irrigated over the summer months. The total nitrogen load produced over a four month operating period would be approximately 0.24 kg N/hog. If the terminal land base were to be planted with a forage crop and harvested twice over the summer, the land base required to spread this nitrogen load would be approximately 1×10^{-3} ha/hog (applying 120 kg N/ha). The volume of effluent would be dependent on local weather conditions.

Area required for final disposal based on nitrogen if a forage crop is planted:

1.0×10^{-3} ha/hog (1 ha per 1000 grower/finishing hogs)

Possible Improvements to Reduce the Wetland Size

It should be noted that loading rates greater than 70 kg N/ha/day for the wetland system could be tested (so that a smaller wetland could be used). The effect of the higher load on the wetland plants and on the effluent quality could be evaluated to determine if this would result in a need for a larger area for terminal land application or if the wetland would fill up with solids.

The ability of a constructed wetland to remove nitrogen is said to be nitrate. In other words, the wetland is limited by its ability to supply the oxygen required conversion of ammonium into nitrate, so that it can subsequently be denitrified to release nitrogen gas. It is likely that if more of the nitrogen supplied to the wetland were in the form of nitrate, rather than TKN (ammonium+organic nitrogen), a higher nitrogen load could be accommodated. This could be achieved by aerating the influent to the wetland, which would also be necessary to lower the BOD_5 so that the surface area (and cost) of the wetland could be decreased. As discussed in the following section, reed beds may have some potential for reducing the required area of the wetland.

III Reed Beds

Reed beds are a type of subsurface flow wetland consisting of a bed of graded media (often gravel or crushed stone) in which emergent aquatic plants (usually common reeds) are planted. The media acts as a physical filter for removing suspended particles and also provides surface area for growth of micro-organisms. The plants supply oxygen to the root zone, creating aerobic micro-zones which promotes nitrification (conversion of ammonium-N into nitrate). Nitrate is removed in anoxic zones by bacterial action which releases nitrogen gas.

There are two general types of reed bed treatment system (RBTS) designs: horizontal flow (HF) and vertical flow (VF).

In a horizontal flow reed bed, the wastewater enters the media bed at the surface of one end, flow horizontally through the bed and is collected at the base of the other end. Since oxygen is transferred only through the plant roots, the ability of HF systems to nitrify wastewater is limited.

In vertical flow reed beds, the wastewater is dosed evenly over the surface of the media bed and is collected by an underdrain. Oxygen is trapped and forced through the bed by the dosing action. VF systems therefore promote nitrification of the wastewater. VF reed beds therefore merit consideration as a method of nitrifying swine manure before it enters an overland flow marsh-pond-marsh type of wetland. The use of such systems may allow for higher nitrogen loading, decreasing the area required for the overland flow wetland.

Much of the development work on reed bed was conducted in the Untied Kingdom. A review of the technology was recently prepared for *Seven Trent Water*. The review's views on the applicability of the technology to agricultural pollutants are summarized in the following passage:

Most agricultural effluents are much too strong to be economically treated using Reed Bed technology alone. However, RBTS have been successfully used to treat weaker dirty waters and have been used for final treatment of some higher strength agricultural effluents following pre-treatment.

The maximum strength of wastewater which can be successfully treated by a reed bed is listed as 2000 mg/L BOD_5 and 650 mg/L TSS.

The estimated BOD concentration of liquid swine manure is 31 000 mg/L (see previous section). However, this estimate may vary depending on the amount of dilution water and the age of the manure. TSS concentration of supernatant of stored swine manure have also been reported as 62 900 mg/L for "high strength wastewater" and 2200 mg/L for "low strength wastewater". Solids in manure slurries are normally reported as total solids or volatile solids rather than suspended solids. Total solids of 4 to 5% (40 000 to 50 000 mg/L) have been reported. The TSS of a sample retrieved from the un-agitated supernatant of a liquid swine manure tank in eastern Ontario was only 710 mg/L.

Pre-treatment of high strength agricultural waste is said to be generally achieved in anaerobic lagoons. As discussed in the previous section, an anaerobic lagoon with a volume of 3.2 m^3/hog may be expected to discharge 0.48 kg BOD_5/hog/day during the summer months (assuming 50% removal). Neglecting precipitation and evaporation and assuming no ground water inflow, the concentration of the lagoon effluent would be 15 500 mg BOD_5/L. Therefore, the lagoon effluent would have to be diluted by a factor of 7.75 if a reed bed were to be used (it could be diluted with rainwater, treated water, ground water or surface water). Since the lagoon would discharge 30.6 L/hog/day, the diluted flow would have to be 237 L/hog/day or 0.237 m^3/hog/day.

Vertical flow reed beds are normally sized on a hydraulic basis at a loading rate of 1 m^3/m^2/day. A vertical flow reed bed would therefore have to be sized at 0.237 m^2/hog. For 1000 grower/finishing hogs, a vertical flow reed bed would be sized at 237 m^2. Each treatment stage should consist of four reed beds, and 40 to 50% BOD removal is said to be achievable per stage. Therefore a total surface area of 0.948 m^2/hog should be capable of reducing the BOD_5 of lagoon effluent from 0.48 kg/hog/day to 0.24 kg/hog/day. Vertical flow reed beds may be considered as a treatment step in a constructed wetland design.

Size of vertical flow reed beds required:

4 beds of 0.237 m^2/hog

Expected performance of reed beds:

0.48 kg BOD_5/day to 0.24 kg BOD_5/day

IV "Package" Wastewater Treatment Plants

The TOAST System

A number of activated sludge systems have been proposed for the treatment of swine manure. A new system, named TOAST™ (Tertiary Oxygen Activated Sludge Treatment), has recently been patented in the U.S. by Engineering Concepts of Mankata, Minnesota. The system is said to "convert organic nitrogen and ammonia into carbon dioxide, water and microbe cells". The process creates two phases, a sludge phase representing about 25% of the volume and a liquid phase representing the other 75%. It is claimed that about half of the nitrogen and most of the phosphorus is removed as sludge (leaving approximately 500 mg/L P and 10 000 mg/L N in the liquid phase). Nitrification is said not to occur (there are no natural nitrifiers in the intestinal tract of swine and the manure is taken directly from the barn; furthermore, the detention time is short-3 to 4 hours). Both the liquid and sludge phases are said not to emit offensive odours.

Since the nitrogen is said to exist as protein rather than nitrate and test results show the effluent is salmonella-free, the inventor, John Petering, suggests that it may be possible to feed the liquid fraction back to the pigs and feed the sludge to cattle (personal communication, June 1997). Petering also suggests the possibility of employing a floor flush system in piggeries similar to that used on some dairy operations rather than using slotted floors. He suggests that by keeping the pigs' skin from drying out, there may be a reduction of skin-dust production (a source of odours as well as a health hazard).

The estimated cost of the TOAST system in $150 000 for use for 300 animal units. Engineering Concepts is interested in licensing the right to the technology to consultants and/or installers.

Despite Petering's reassurances, a certain degree of reluctance may be encountered with regards to feeding the liquid effluent back to the pigs, due to fears of spreading disease. If this is the case, the liquid fraction may still have to be spread or irrigated. If the liquid cannot be re-fed to swine, the main advantage of the system would be odour reduction, rather than a reduction in land base requirements for spreading.

A prototype TOAST system is currently undergoing testing by the University of Minnesota. The system appears to be very effective in reducing odours.

Silsoe's "Dirty Water" Treatment System

The United Kingdom's Silsoe Research Institute has conducted trials on the aerobic treatment of swine manure. Providing aeration reduces odours emanating from the manure tank and from manure as it is being spread.

Extensive aeration can also be used to reduce nitrogen levels in manure. Part of the nitrogen is conserved as biomass (tied up in the cells of microorganisms, much of which settles out), a fraction is conserved as nitrate, and a fraction is lost through volatilization. If aerobic cycles are alternated with anaerobic cycles under well controlled conditions, it is possible to promote nitrification/denitrification processes which result in the removal of harmless nitrogen gas. However, the Silsoe research has indicated that greenhouse gases such as nitrous oxide, N_2O are also produced. Much of the research focuses on defining the conditions which promote the production of N_2 rather than NO_x (greenhouse) gases.

Depending on the extent of treatment to be achieved (whether treated for odour reduction or for nitrification and subsequent denitrification), the cost of providing aeration was estimated to range between £1.60 and £10.50 per pig produced (over $3 to $21) in the U.K. in 1991.

V Evaporation

It is conceivable that the liquid fraction of the manure could be reduced by simply providing an overflow from the lagoon or manure tank into a shallow evaporation basin. However, this may be expected to cause odour problems as volatile organic acids and other odour causing gases volatilize.

VI Pelletizing

A swine finishing and poultry broiler operation in the Fraser Valley of British Columbia conducted trials in which swine manure was combined with broiler litter and pelletized. The pellets were then transported to Alberta where they were marketed as commercial fertilizer.

The pelletizing process was carried out on a small scale at Agriculture Canada's research station an Agassiz in order to determine the feasibility of such a venture. The trials were economically promising.

POTENTIAL TECHNOLOGIES WHICH COULD BE USED IN MOBILE TREATMENT UNITS

To avoid forcing each operation to bear the capital costs of an independent treatment system it may be possible to offer a manure concentration *service* rather than marketing a treatment system. The overall goal would be to divide the manure into tow fractions: a small volume of concentrated manure (either solid or liquid) which could be hauled at a much lower cost than is currently the case; and a larger fraction of dilute manure which could be spread at high loading rates on a small area of land around the livestock facility. A trained custom operator would transport the system from farm to farm, treating the contents of each manure tank in batches. This would eliminate the need for each farm to own and operate its own treatment system and would make use of existing storage facilities.

Candidate technologies for mobile batch treatment systems would have to provide treatment in a relatively short time frame so that the operator could quickly move from farm to farm. It may be possible to adapt some technologies which have been tested for on-farm use in a central treatment plant. Some candidate technologies are discussed below.

I Chemical Addition

Chemical precipitation has been tested as a method of separating solids and/or nutrients from swine manure and could easily be adapted as part of a mobile treatment system.

Lime and Alkaline By-products

A simple method of reducing the nutrient concentration of the liquid fraction of swine manure is add lime (or alkaline industrial by-product containing calcium or magnesium, such as fly as or cement kiln dust) and provide agitation. By increasing the pH, dissolved ammonium is converted to ammonia gas which is stripped from the solution by agitation. At high pH, calcium and magnesium react with phosphorus forming insoluble compounds which precipitate. This leaves a liquid fraction with greatly reduced nutrient value which can then be spread on a smaller land base. During spreading, the liquid would have a less offensive odour.

This type of treatment has been proposed in Canada and the U.S. However, it has some serious drawbacks. During agitation, while ammonia and other gases are released, severe odour problems may be expected. Furthermore, the release of ammonia from livestock manure has been linked to acid rain. In Europe (especially the Netherlands), the prevention of ammonia volatilization is usually considered essential for an acceptable manure management system.

“Domtar lime” a by-product of the company’s fine paper manufacturing, could conceivably be used to strip ammonia. However, such a practice may provoke a negative reaction from environmentalists concerned over air pollution.

Metallic Salts

Metallic salts such as ferric chloride and alum, can be used to precipitate suspended solids and phosphorus. Since they have a depressing effect on pH, they should reduce ammonia losses through volatilization - alum has been used to reduce ammonia losses in poultry boiler litter in the U.S.

A metallic salt was used in combination with centrifugation in the German mobile treatment system named KIEL discussed below in the section on centrifugation.

Magnesium

It is possible to precipitate ammonium and phosphorus from swine manure by adding magnesium and adjusting the pH above 8. This is the principle behind two collective treatment systems tested in Europe: the AVDA system in France and the MAP system in Germany. The magnesium, ammonium, and the phosphate are said to react in a 1:1:1 stoichiometric ratio. Since the manure contains an excess of ammonium compared to phosphate, it is necessary to provide additional phosphate in addition to the magnesium in order to precipitate all of the ammonium. The European systems are magnesium oxide and phosphoric acid. As much as 98% of the ammonium and 99% of the phosphorus can be removed from the liquid fraction.

An estimate of the chemical requirements can be made using the suggested 1:1:1 stoichiometric ratio of ammonium, magnesium and phosphate. Using the ratio, it is estimated that over 5500 kg of Mg and over 6500 kg of P would have to be provided to remove all of the ammonia produced by a 1000 pig finishing operation over 200 days. Tests would have to be carried out to determine ammonia removal efficiencies with different sources and doses of magnesium and phosphorus. It should be noted that above pH 8, there will be some loss of volatilized ammonia. Ammonia volatilization would probably be of less concern in North America than in Europe.

It may be possible to use dolomitic lime as an inexpensive source of magnesium. A phosphorus additive may prove to be more expensive.

Bench scale trials were conducted using dolomitic lime and phosphoric acid. No appreciable ammonia nitrogen was achieved. It is possible that an insufficient amount of magnesium from the dolomitic lime dissolved in the wastewater, and therefore not enough magnesium was available to react with the ammonium and phosphorus.

Commercial Polymers

Polymers can be used to aid solid-liquid separation of wastewaters including liquid livestock manure.

In laboratory trials conducted at the University of British Columbia, the polymer PERCOL 728 was tested for its ability to remove suspended solids and chemical oxygen demand from the supernatant of two swine manure tanks. The polymer was found to be effective for use with “high strength” wastewater in combination with settling. At a dosage of 50 mg/L a suspended solids (TSS) removal of 94% and a chemical oxygen demand (COD) removal of 74% were achieved for a wastewater with an initial suspended solids concentration of 62 900 mg/L and a chemical oxygen demand of 59 400 mg/L. However, no improvement was reported in suspended solids and chemical oxygen demand removal for a low strength wastewater (TSS=2200 mg/L & COD=8460 mg/L). If centrifugation was provided, the addition of the polymer did not improve the treatment for either high strength nor low strength wastewater.

A representative of Allied Colloids Ltd., the producer of the PERCOL polymer series, suggested testing several polymers for solid-liquid separation of swine manure: PERCOL 757, PERCOL 753, PERCOL 728 and PERCOL 721. Preliminary bench scale tests carried out on a weak swine manure wastewater (TSS=700 mg/L) did not show any improvement in settling.

Drew Chemicals Ltd. suggested testing the following polymers: Chargepac Series: 5, 20, 36, 60 and Drewfloc 2270. These tests have yet to be conducted.

II Centrifugation

Portable centrifuge units are available for solid/liquid separation, and have been used for other applications (including septage de-watering). A centrifuge could conceivably be used as one step in a treatment system, assuming that a good level of solid-liquid separation could be achieved.

Dr. Lo of the University of B.C. reported good TSS removal by centrifugation in laboratory trials. However, other researchers who have tested centrifugation of swine manure (personal communications with Dr. John Ogilvie and Dr. Naveen Patni, June 1997) have indicated that results have been disappointing (the manure is sticky and tends to retain water).

Even following successful separation by centrifugation, a relatively high level of ammonia-N may be expected in the liquid fraction, as it is highly soluble. Centrifugation could conceivably be used in conjunction with chemical treatment to separate solids and nutrients from the liquid fraction of swine manure.

The KIEL Experiment

A mobile system combining centrifugation, chemical treatment and flotation processes was tested in Germany in the early 1990's. In what was known as the KIEL experiment, the liquid fraction, separated by centrifugation, was treated with $FeClSO_4$ (dosing was 0.1 to 1 kg of Fe^{3+} per m^3 of wastewater), before flowing into a static mixer where an anionic polyelectrolyte was added. The resultant floc particles were removed in a flotation unit. Part of the floc was recycled to the start of the treatment process.

The system was reported to achieve the following removal rates for the liquid fraction of swine manure: 53% total nitrogen (TN), 85% phosphates (as P_2O_5) and 25% potassium (as K_2O).

The capital cost of the mobile unit was $800 000; fixed costs were estimated to be $160 000 to $200 000 per year; and variable costs were approximately $3.20 per cubic meter. The minimum cost to treat 40 000 m^3 per year was estimated to be $8.60 per m^3 (this includes worker wages at $40 000 per year but does not consider the cost of composting the solid fraction). These costs were not comprehensive with storage and long distance hauling and the process was abandoned.

Representatives from Alfa-Laval Inc. have indicated that they may be interested in providing a centrifuge for a swine manure treatment project.

III Membrane Systems

Since membrane modules are easily adaptable as portable treatment units, the possibility of using a membrane technology for concentrating swine manure has been included in this section, although the units used in the trials described below were not mobile.

An on-farm, membrane based treatment unit was proposed in British Columbia in 1995. The design made use of technologies developed by Zenon Technologies (for other applications) which incorporate biological digestion and membrane separation (known as ZenoGem™ and ZeeWeed™). The effluent from a biological reactor was to be forced through an ultrafiltration module which would remove all bacteria and suspended matter while allowing the dissolved nutrients to pass through. The permeate (the liquid passing through the membrane) from the ultrafiltration module was to be concentrated in reverse osmosis unit. The product would be a concentrated solution of nitrogen, phosphorus and potassium which could be marketed as a liquid fertilizer, since it would have no effective odour and would be pathogen free.

Due to personal problems of the collaborating producer, the original test site had to be abandoned. A second producer decided to proceed with similar trials, using membrane modules manufactured by a different company. In this design, the bioreactor was replaced with a sequencing batch reactor (SBR), but ultrafiltration and nanofiltration modules are still included. Some limited trials have been attempted to date and there has evidently been some difficulty with suspended solids in the effluent of the SBR. However, the system is still being "fine tuned".

According to Mr. Richard Vankleeck, of the B.C. Ministry of Agriculture Fisheries and Food, the Zenon membrane technology seems to show a great deal of promise, since it can handle a much higher suspended solids loading than can conventional ultrafiltration modules (including the module currently being tested), and deserves further testing. Its adaptability to a mobile, contractor operated system is unclear.

IV Ammonium Adsorption

Ammonium can be removed through adsorption, rather than by precipitation or gas stripping. A University of Guelph study identified the following natural materials for ammonium adsorption: clinoptilolite (a zeolite), bentonite, vermiculite and peat. These materials were proposed as additives to manure tanks to reduce ammonia losses from the manure tank and to control the release of nitrogen from manure applied to the field. Since the adsorption material was to be applied to the field along with the manure, it was decided to use only "naturally" occurring materials.

In a related study, clinoptilolite was used to adsorb air-borne ammonia in poultry houses. An ion exchange column, filled with zeolite and "spiked" with nitrifying bacteria, was designed and tested at an experimental barn operated by the University of Guelph. The idea was to adsorb the ammonia onto the zeolite, then promote conditions in which bacteria would convert the adsorbed ammonia into nitrate then nitrogen gas. This would effectively free new adsorption sites and allow continued removal of ammonia. Although the column removed ammonia, it was not definitively proven that the nitrifiers liberated adsorption sites.

Linking these two ideas related to ammonium adsorption could be valuable to the development of a system for reducing the nitrogen content of swine manure. If an adsorption medium could be used to remove ammonium from the liquid fraction of the manure, then re-generated by nitrification-denitrification, a number of methods would be possible to treat swine manure. The liquid fraction of a manure tank could be filtered through a bed of adsorption medium (possibly following some type of pre-treatment to reduce its clogging tendency). Alternatively, the adsorption media could be mixed with a tank containing pre-separated liquid manure. The spent adsorption media could then be biologically regenerated on-site.

The ammonium adsorption capacity of the zeolite, clinoptilolite, is reported to be approximately 2meq/g but the adsorption capacity may be expected to vary depending on the source of the mineral (since it is naturally occurring) and the concentration of ammonia in the liquid from which the ammonium is to be adsorbed. Assuming the reported adsorption capacity, it would require approximately 64 kg of clinoptilolite to adsorb the ammonium contained in one cubic meter of manure. It would therefore be necessary to recover the clinoptilolite rather than spread it on the fields with the manure. The mass of clinoptilolite required would probably preclude its use in a mobile system.

High capacity synthetic ion exchange resins are also available for ammonium adsorption. These resins are normally recharged with sodium chloride (salt) or sodium hydroxide (caustic soda). Synthetic resins may be better suited for a mobile type of treatment than would be the natural zeolite (it would be preferable if they could be recharged biologically).

Preliminary laboratory trials were carried out using clinoptilolite to adsorb ammonium from liquid swine manure.

PRELIMINARY LABORATORY TIALS ON CHEMICAL TREATMENT

I Liquid Swine Manure Tested

A sample of liquid manure was taken from a local farrow to weaning operation with approximately 300 sows. A 40 L grab sample was taken from the supernatant (the liquid fraction) only of the manure tank, using a bailer sampler which collected liquid from approximately the top 1.2 m of the 3 m deep tank. The tank was not agitated prior to taking the sample. It is estimated that the liquid supernatant represented approximately 85% of the volume of the tank.

II Jar Tests - Suspended Solids Removal

Objective

Jar tests were conducted to determine if removal of suspended solids by settling could be improved by chemical addition.

Method

Jar tests were carried out using a Phipps-Bird six paddle stirrer. Round one litre beakers were filled with the liquid swine manure and agitated at 130 rpm. Different doses of coagulant were added, and the rapid mixing continued for 5 minutes. The mixing was then slowed to 30 rpm for 30 minutes. This was followed by a 1 hour settling period. Samples were then drawn from the supernatant of the beaker using a 60 mL syringe.

Results

In the first set of jar tests, 50 mg/L doses of the commercial polymers PERCOL 757, PERCOL 753, PERCOL 728, and PERCOL 721 were added to one litre samples of liquid swine manure. The samples treated with PERCOL 757 and PERCOL 753 did not show any visual signs of improved solid/liquid separation and were not tested further.

Jar tests were then conducted using PERCOL 721 and PERCOL 728 as coagulants.

Table 1: Jar Tests using PERCOL 721, PERCOL 728 and dolomitic lime + phosphoric acid as coagulants

Coagulant	**Dose** (mg/L)	**TSS** (mg/L)
Raw Wastewater	0	700
Percol 728	25	560
Percol 728	50	540
Percol 721	10	740
Percol 721	25	760
Percol 721	50	920

Another set of jar tests was conducted using ferric chloride and a combination of dolomitic lime and phosphoric acid as coagulants.

Table 2: Jar Tests using Ferric Chloride and a Combination of Dolomitic Lime and Phosphoric Acid as Coagulants

Coagulant	**Dose** (mg/L)	**TSS** (mg/L)
Raw Wastewater	0	720
Ferric Chloride	2000	125
Ferric Chloride	4000	210
Ferric Chloride	8000	115
Dolomitic Lime + Phosphoric Acid	33 g lime + 8 mL acid	224

Samples of the raw liquid swine manure, the supernatant and the sludge of the manure treated with dolomitic lime + phosphoric acid and the manure tested with PERCOL 721 and PERCOL 728 were preserved with sulfuric acid and sent to a private laboratory for analysis of ammonia-N. Results are presented in Table 3.

Table 3: Ammonia-N Concentration of Treated Swine Manure Samples

Treatment	**Ammonia-N Concentration** (mg/L)
Raw Wastewater	2173
Dolomitic lime + Phosphoric Acid	
Supernatant liquid	2080
Sludge	2061
PERCOL 721	1991
PERCOL 728	2083

Discussion

At the doses tested, ferric chloride and the combination of dolomitic lime and phosphoric acid provided the best suspended solids removal. A lower dose of ferric chloride may have sufficed.

The 33 g/L dose of dolomitic lime and 8 mL dose of phosphoric acid were based on providing a 1:1:1 ratio of magnesium:ammonium:phosphate as used in the European systems (in which magnesium oxide was used). Since the lime was only 12% magnesium, an excessive dose was required. The addition of phosphoric acid and dolomitic lime lowered by the pH from approximately pH 8.2 and pH 5.4. The pH was raised to pH 8.3 with the addition of 14 mL of NaOH in order to promote the precipitation of magnesium ammonium phosphate. However, although the use of phosphoric acid and dolomite resulted in good suspended solids removal, ammonium was not precipitated (supernatant and the sludge concentrations were almost the same as that of the untreated sample and of the samples treated with polymer).

It is possible that the lack of ammonium removal may have been due to a competing reaction in which the calcium in the dolomitic lime removed the phosphate before it could combine with the magnesium and ammonium.

III Ammonium Adsorption Using Clinoptilolite

Objective

As a preliminary method of determining if the use of the clinoptilolite had potential for removing ammonium from liquid swine manure, a simple test was carried out.

Method

90g (approximately 100 mL) of clinoptilolite and 150 mL of liquid swine manure were added to an Erlenmeyer flask. The flask was sealed with a rubber stopper and left undisturbed for two hours. At the same time, a second Erlenmeyer was filled with 150 mL of liquid swine manure and sealed with a rubber stopper. After two hours, the pH was measured for both samples of liquid swine manure, and the samples were preserved with sulfuric acid, and sent to a private laboratory to be analysed for ammonia + ammonium nitrogen.

Results

The following table presents the ammonia-N concentrations of a sample of the original liquid swine manure ("raw manure"), a sample added to an Erlenmeyer flask for two hours ("control"), and a sample exposed to clinoptilolite for two hours.

Table 4: Ammonia-N Removal by Adsorption onto Clinoptilolite

	Raw Manure	**Control**	**Manure Treated with Clinoptilolite**
pH	8.2	8.2	8.3
ammonia-N (mg/L)	2173	2106	1523

Discussion

According to the literature, the ammonium adsorption capacity of clinoptilolite is approximately 2 meq or 36 mg of ammonium per gram of clinoptilolite. It should therefore be possible to remove 3240 mg of ammonium with 90 grams of clinoptilolite. Since the total mass of ammonium in the control sample was 316 mg ammonium (2106 mg/L x 0.150 L) and the mass of ammonium in the treated sample was 228 mg ammonium (1523 mg/L x 0.150 L), even if it is assumed that ammonia volatilization was minimal, the clinoptilolite only removed 88 mg of ammonium.

It should be noted that this is not a recognized standard test. It may be necessary to circulate the liquid manure through the clinoptilolite to improve ammonium removal. To better measure the adsorption capacity of the clinoptilolite, a standard ion exchange column should be set-up.

The conclusions and recommendations of the report were expanded upon and are presented as a summary.

CONCLUSIONS AND RECOMMENDATIONS

A number of solids separation and nutrient removal technologies have been developed for municipal and industrial wastewater treatment. These can be adapted to the treatment of swine manure. The construction of central treatment plants is not recommended since the strategy was largely unsuccessful in Europe. In choosing the most promising technology, the conditions which will be encountered on the farm must be taken into account. If a permanent on-farm system is to be installed, it would be preferable that the required operator attention be kept to a minimum. Technologies requiring more operator expertise can be considered if a contractor operated mobile treatment system is employed.

Several technologies were identified in this preliminary report. A detailed analysis including physical experimentation and a market analysis would be required to select the best technologies. However, it is possible to identify a few technologies which could be readily tested on-farm by Alfred College and Stantec Consulting in collaboration with other research institutes and/or private enterprises.

Treatment strategies identified in this report which show the greatest potential for on-farm testing are (in no particular order):

1) Composting to Remove Water:

The evaporation of excess of water in a compost pile seems to be a relatively simple solution to reduce the volume of water to be transported and spread. Composting would require some operator attention but little expertise once guidelines are established. The project could almost certainly be carried out in collaboration with Agriculture Canada (Naveen Patni) and Ridgetown College (Jim Morris and Ron Fleming).

Advantages

1. We have expertise available to us (Naveen Patni etc.)
2. Will not require excessive operator expertise, once guidelines have been developed.
3. Other trials have shown that it is possible to evaporate all of the liquid with the heat of the compost. This reduces transportation costs.
4. The process produces a useful soil amendment.
5. It may be possible to pelletize the compost so that it can be shipped long distances and marketed to greenhouses etc. This would tie in with another of our projects.

Disadvantages

1. Ron Fleming does not believe that the forced aeration system they are testing is ready for testing on a commercial farm.
2. Passive aeration systems may be too labour intensive.
3. There may be some concern over odour, although the compost is expected to adsorb much of the odour causing gases.
4. A composting project proposal would certainly not be unique. A number of other companies will write similar proposals.

2) Ultrafiltration/Reverse Osmosis Membrane Systems:

Mr. Rick Vankleeck of the B.C. Ministry of Agriculture, Food and Fisheries was involved with a group which had already established a protocol for testing a system developed by Zenon Technologies. In 1995, the group, including a private consulting firm (Hill, Murray and Associates), Zenon and Rick Vankleeck provided technical information for a proposal which was submitted to Ontario Pork by Alfred College. It may be possible to re-initiate this project, especially considering that the B.C. trials had to be cancelled (because of a personal problem suffered by the cooperating producer).

Advantages:

1. Most of the nutrients would be recovered and put to good use. It may be possible to recover part of the cost by marketing the concentrate as a liquid fertilizer.
2. It would be possible to re-use the product water from the reverse osmosis unit in the barn.
3. The technology is easily scaled up or down.
4. With a membrane system, it may be possible to design a mobile system and to offer a swine manure treatment service rather than trying to sell individual treatment systems to farmers. This would generate repeat business for the custom operator and allow the producers to focus on farming.
5. Membrane modules require little land area.
6. It is claimed that the Zenon system can handle approximately 5% TSS.
7. Funding sources will receive few similar project proposal. If the Zenon biological reactor + ultrafiltration + reverse osmosis system is proposed, it would likely be seen as unique.

Disadvantages:

1. We have only limited experience with membranes, and much of the expertise would be from outside sources.
2. Other membrane systems have tended to foul.
3. There have been no published trial results of the Zenon system for swine manure.
4. Relatively inexpensive to test.

3) Constructed Wetlands and Reed Beds: Stantec Consulting and Alfred College both have experience and credibility in the design of such systems. It would have to be determined if a reed bed would be a suitable method of pre-treating the manure so that it could be handled in a wetland.

Advantages:

1. We already have expertise in the design, construction and monitoring of wetlands.
2. Wetlands would require little operator attention.
3. There have been some successful systems constructed in the U.S.
4. The proposal could include the testing of various “pretreatment systems”, which may give us a chance to evaluate other technologies.
5. Other groups will submit proposals, but we should be able to compete with them based on our past experience.

Disadvantages:

1. Odour control may be perceived as a problem by the funding bodies.
2. Many academics will object because nutrients would be “wasted” rather than utilized on the land (John Ogilvie for example). The idea of treating manure to get rid of nutrients contradicts what ministries of agriculture have been preaching to producers: “Manure is a valuable nutrient resource, not a waste material to be disposed”.
3. Manure would have to be stored over the winter.
4. Wetlands require land which is valuable in many regions with large livestock producers.
5. Large lagoons may be required for pretreatment. These have received a lot of bad press, particularly in the U.S. (i.e. *60 minutes*).
6. Relatively expensive to test (involves on-site construction).

4) Chemical Precipitation: The addition of a coagulant to promote sedimentation of solids and nutrients would appear to be a good candidate technology: it is simple, relatively inexpensive and previous trials have been relatively successful. If further nutrient removal from the liquid fraction is deemed to be advantageous, chemical precipitation can be combined with other nutrient removal technologies so that the necessary land base for spreading can be further reduced. Although the initial laboratory trials were disappointing, a number of other strategies could be tested at relatively low cost in the laboratory.

Advantages:

1. Very simple.
2. Can easily be combined with other treatment processes for mobile or stationary systems.
3. Relatively inexpensive to test.
4. Easily scaled up or down.

Disadvantages:

1. Not a complete treatment.
2. Is probably too expensive to implement (high doses of chemicals are required).

5) **Ammonium adsorption should also be considered**.

Although naturally occurring zeolites do not provide sufficient adsorption capacity to make them practical for mobile treatment systems, they can be tested as high performance subsurface filters. Other materials such as LECA or shale may also be tested. The idea would be to provide a number of adsorption beds so that they can be alternatively loaded and rested. During the loading period, the ammonium would be adsorbed onto the media and during the resting period (aerobic), it would be nitrified and the adsorption sites would be regenerated. The effluent may prove to be more nitrified than the effluent of a conventional reed bed, in which most of the ammonium would pass right through. Nitrified effluent could then be passed through a denitrification system. Note that this may prove to be a good option for pretreatment for a wetland, since a wetland's ability to remove nitrogen is said to be nitrification limited.

A synthetic ion exchange resin with a high ammonium adsorption capacity may be considered as part of a mobile treatment system. The idea would be to pretreat the liquid manure to remove solids (a mobile screw-press could be used). The liquid would then be treated in a mobile ion exchange reactor to remove ammonium (and phosphorus, if necessary). Treated liquid would be irrigated. The resin would be taken off site to be recharged at a central location, either chemically or biologically (by spiking it with nitrifying bacteria). The regenerate would be recovered to be marketed as a liquid fertilizer.

Advantages:

1. Ion exchange technologies would be easily incorporated into designs which include other components (such as constructed wetlands).
2. Standard methods exist for comparing ion exchangers. We already have most of what would be required in our lab. The tests would be relatively inexpensive.
3. Tests could be carried out which would lead to either a mobile system or an on-farm system.

Disadvantages:

1. There is a lack of previous research (we should order a literature search from a library).
2. The chemical used to regenerate a synthetic resin would have to have to negative effects on agricultural land - NACl could not be used.
3. The liquid "fertilizer" recovered from a synthetic resin may still have a bad odour. If this were the case, it would be difficult to market.

APPENDIX E

DESIGN EXAMPLE FOR SEPTAGE WASTE

Design Example for the Treatment of Septage Waste
Using Constructed Wetlands
(by: Olvier Fankhauser, Alfred College)

INTRODUCTION

The following Design Example is for an actual site located in Southwestern Ontario, in the Towsnhip of Stephen, approximately 8 km south east of Grand Bend. The property in question is that of Mr. Andy O'Brien of Grand Bend Sanitation. The purpose of this design example is to outline the general design of a simple natural system to treat septage. Septage is the material pumped from a septic tank when it is emptied. Under current practices, septage and holding tank wastes are either hauled to wastewater treatment plants or applied on land. However, as provincial governments reduce subsidies to wastewater treatment plants, tipping fees for septage haulers will increase. It is also becoming more difficult to apply septage on land, due to more stringent regulations and public pressure (i.e. complaints about odours). Thus, it will become more important to find an alternative to conventional septage management. This report will propose a new way to treat septage.

SEPTAGE CHARACTERISTICS

Septage is characterized by concentrations of pollutants that are 6 to 80 times higher than in sewage (EPA, 1984). It is anaerobic and odoriferous, which might cause problems for a treatment plant in a residential area. It contains hair, plastic material, food particles, sand, gravel and other coarse materials that might clog and wear pumps and conduits. Its grease content may cause problems for a treatment plant based on natural systems. The presence of detergent surfactants (LAS=linear alkyl sulfonate) may cause large quantities of foam to be produced by agitation. The material has a high concentration of solids, giving it an appearance similar to sewage sludge. However, it is more difficult to treat than sewage sludge, because it is more inert; the more readily degradable organic material is decomposed for the two to five years in the septic tank before it is hauled away (Teal & Peterson, 1993).

Table 1: Characteristics of septage (EPA, 1984)

Parameter	Septage (mg/l)	Sewage (mg/l)	Septage/sewage ratio
TS	40 000	720	55
TVS	25 000	365	68
TSS	15 000	220	68
VSS	10 000	165	61
BOD_5	7 000	220	32
COD	15 000	500	30
TKN	700	40	17
$N\text{-}NH_3$	150	25	6
TP	250	8	31
LAS	150	N/A	N/A
Grease	8 000	100	80

CONVENTIONAL MANAGEMENT

Management of septage can be separated into three categories (EPA, 1984): land disposal, co-treatment in a wastewater treatment plant and independent treatment (composting, stabilization lagoon, aerobic or anaerobic digestion, lime stabilization, chlorine oxidation). The two first categories are the most common. Some pre-treatment (screening, grit removal) is usually performed at the receiving station.

Land application

Land application takes advantage of the soil and vegetation's ability to remove pollutants. Application can be done with spray irrigation, incorporation, ridge, furrow systems and overland flow systems. According to the regulations, the sludge should not be applied to land which will be used within six months by grazing domestic livestock. Fruits and vegetables should not be planted until eight months following the application. If the sludge is not covered with earth, a twelve month period should be adopted. In order to apply septage, the land must be licensed as class 7 and must comply with certain criteria (topography, proximity of wells and surface water, soil conditions, depth to groundwater and bedrock). Thus, this system is simple and cost-effective, but more stringent regulations and public pressure make it increasingly difficult to use. In addition, this method is weather dependent.

Co-treatment in wastewater treatment plants

Septage can be added to the liquid or to the sludge stream of wastewater treatment plants. It was demonstrated that the dilution of septage (1-2%) in sewage increases its settling characteristics, which has been shown to be low compared to other products. Since a large fraction of its organic content is associated with suspended solids, the primary clarifier will reduce its BOD_5 by 50-60%. In some plants, septage is added to the sludge stream. However, due to poor dewatering characteristics, septage should first be chemically or biologically conditioned. Septage treatment in wastewater treatment plants will become more costly in the near future, as subsidies will be drastically reduced.

ALTERNATIVE MANAGEMENT

Constructed wetlands

"Constructed wetlands, in contrast to natural wetlands, are human-made systems that are designed, built, and operated to emulate natural wetlands or functions of natural wetlands for human desires and needs" (Hammer, 1995).

In wetlands, four components act together to reduce the pollution. These are the vegetation, the microorganisms, the soil, and the water column. For example, vegetation has four effects: 1) it increases sedimentation by reducing flow velocities; 2) it provides an environment for the microorganisms; 3) it brings oxygen to the media through the roots and 4) it creates and maintains a litter-humus layer that is highly reactive. The vegetation also takes up a small amount of the nutrients, but those are returned to the system after the plants die. Microorganisms alter the pollutants to obtain nutrients, oxygen or energy to carry out their life cycles. The soil acts as a reactive surface area for complexing cations, anions and other compounds and provides attachment surfaces for the microorganisms.

Constructed wetlands have largely been used to treat animal wastewaters. They usually have the following set-up: marsh/pond/marsh/overland flow system. The emergent marshes are shallow basins (10-20 cm water depth) with densely growing vegetation. The pond is a 0.75 to 1 meter deep aerobic/oxidation lagoon. The first marsh promotes ammonification, the aerobic pond transforms the ammonia into nitrites and nitrates, and finally the last marsh acts as a denitrifier. The overland flow system traps suspended solids that result from the treatment, improves nitrogen removal and functions in some cases as an irrigation area. These four steps follow a pre-treatment, as constructed wetlands are essentially designed to polish effluents and should not be fed with raw wastewater (BOD_5 should primarily be reduced to 400 mg/l). Furthermore, pretreatment with lagoons accomplishes pollutant reduction more efficiently than a stand-alone wetland system (Hammer, 1992).

For example, a wetland designed to treat dairy cattle feedlot and solid manure pile runoff (Weil *et al*., 1997) managed to reduce pollutant concentration dramatically in Embrun, Eastern Ontario (table 2). The system is designed in the following way. The manure pile runoff is collected in an anaerobic lagoon before entering the system at a controlled rate. The feedlot runoff is first treated with an overland flow system. These two flows then enter a stabilization pond and a marsh/pond/marsh/overland flow system. The system was designed for a loading rate of 100 kg/ha/day of BOD_5 for the stabilization pond and 3 kg/ha/day of TKN for the rest of the system.

Table 2: pollutant concentration reduction of a wetland to treat dairy runoff (Weil *et al*., 1997)

	BOD_5 reduction		TKN reduction		TP reduction	
	In cell	Overall	In cell	Overall	In cell	Overall
Facultative pond	91.6 %	91.6 %	88.5 %	88.5 %	81.2 %	81.2 %
Marsh 1	22.0 %	93.5 %	10.3 %	89.7 %	18.6 %	84.7 %
Aerobic pond	73.7 %	98.3 %	57.6 %	95.6 %	48.3 %	92.1 %
Marsh 2	24.6 %	98.7 %	49.2 %	97.8 %	40.4 %	95.3 %
Filter strip	29.5 %	99.9 %	- 27.0 %	99.7 %	-53.5 %	99.9 %

Thus, constructed wetlands could be used to polish the effluent from a septage treatment system. Their principal disadvantage is their high land requirement as compared to other treatment systems.

CASE STUDY: SITE SPECIFICATIONS

The study site is located in Southwestern Ontario, about 8 km south east of Grand Bend. Mr. Andy O'Brien, president of Grand Bend Sanitation Inc., owns a 20 ha parcel located in Stephen Township, Concession XIX, about 1.6 km north of Highway 81. Approximately 8 ha are currently registered as class 7 for septage land application.

A preliminary hydrogeological investigation was performed on-site (Beatty Franz and Associates, 1997). The nearest municipal drain is located over 300m to the southwest of the property. The nearest wells are located more than 500m to the east of the proposed treatment system. The soil is composed of 25cm topsoil, 15-40cm thin, medium-grained sand and silty clay with some sand and stones. The silty clay is composed of 60% silt and 25% clay. This material has a very low hydraulic conductivity. According to the investigation, this site appears to be favourable for the construction of the proposed septage system. However, the sides of the proposed system should be lined with compacted till to seal the more permeable sand and weathered till units in the upper layers.

A climatic analysis was performed based on precipitation and evaporation data obtained from the Ontario Climate Centre (Exeter station: 1961-1996). In order to limit risks of overflow, net precipitation (precipitation-evaporation) should be taken into account when computing the storage volume of the different components. For further risk reduction, the net precipitation that is used in the design should have a probability of occuring only once in a period of ten years (wet year). The climatic data is presented in table 3.

Table 3: Total and net precipitation at Exeter, Ontario

	Mean precipitation (mm)	10-year high precipitation (mm)	Mean net precipitation (mm)	10-yr high net precipitation (mm)
Winter	603	713	494	606
Annually	984	1155	332	510

DESIGN

The objective of this project is to provide a simple and cost-effective septage treatment system with low labour and monitoring requirements. As mentioned above, land application and co-treatment in wastewater treatment plants will become either more costly or more difficult in the future. Reed beds, lagoons and the solar aquatic system (SAS) are potential alternatives. A preliminary design was conceived which included a receiving station, a pre-treatment, an anaerobic lagoon, a reed bed, a facultative pond and a marsh/aerobic pond/marsh/overland flow system. This system would produce a polished effluent, but the area needed and the costs associated are excessive. It was decided to review the design and produce an effluent that can be used for irrigation onto agricultural land. The proposed treatment system is a low cost technology combining the advantages of lagoons and wetlands, like in the SAS system, but without the costs of intensive aeration and a greenhouse.

Design principle

The proposed system is composed of the following: receiving station/pre-treatment/anaerobic lagoon/facultative pond/aerobic pond/marsh/irrigation. The natural treatment system proposed for Grand Bend Sanitation is designed to produce an effluent to be irrigated on 1 or 2 ha of grass forage having the following nutrient requirements (OMAFRA recommendations in Eastern Ontario for clay soils):

Nitrogen (as N) :	130-150 kg N/ha
Phosphorus (as P_2O_5)	50-90 kg P_2O_5/ha
Phosphorus (as P)	20-40 kg P/ha
Potassium (as K_2O)	0-30 kg K_2O/ha
Potassium (as K)	0-25 kg K/ha

The proposed design is inspired by the Embrun constructed wetland (Weil *et al.*, 1997). However, since the Embrun system was designed to discharge into a meadow and eventually flow into a creek, its effluent criteria had to be more strict. The effluent from Grand Bend will be irrigated onto agricultural land. As a result, the proposed system will be more compact and less costly per cubic metre of wastewater treated. The target effluent quality in Embrun and Grand Bend are listed below:

	Embrun	**Grand Bend**
BOD_5	< 20 mg/l	N.A
TN	< 10 mg/l	100 mg/l for 1 ha irrigated
TP	< 1 mg/l	30 mg/l

The TN of the septage wetland effluent must be 100 mg/l if 1 ha of land is available for irrigation. It can be increased by 100 mg/l for each additional available hectare. The maximum at Grand Bend is 200 mg/l, as additional land is not available. The stringent storage requirements for the anaerobic lagoon will provide sufficient reduction of TSS and BOD_5. This combined with the high TN target in the system effluent should result in a compact and inexpensive system overall.

Design boundary conditions

- The septage characteristics are based on the values proposed by the EPA (1984) and given in table 1. The parameters which are most important for design purposes are: BOD_5 = 7 000 mg/l, TSS = 15 000 mg/l, TKN = 700 mg/l and TP = 250 mg/l.

- The total volume of septage to be treated is 1 350 m^3 per year. According to the EPA (1984), loadings are lower in the winter. Therefore, it is assumed that loading is 45% in the spring and summer, 35% in the fall and 20% in winter. The storage will have to store the fall, winter and early spring septage for a total estimated at 66% of the yearly production: 890 m^3.

- A possible scenario, which must be checked for treatment efficiency, is that the anaerobic lagoon would store and treat 890 m^3 (240 days) + 2 years of sludge at the bottom. The active treatment period beyond the anaerobic lagoon is 125 days between (from the end of May to the end of September).

- During an average winter, 0.7 m of precipitation will dilute the waste. The impact of dilution in winter is greatly offset by the concentration in summer due to evaporation.

- The design is governed by the following parameters (from most to least important): cost, ability to store in winter, treatment efficiency. Efficiency was rated least important, because the effluent is irrigated onto farm land.

Septage pretreatment

Before entering the treatment system, the septage should be pretreated. This will be done either at a receiving station or with the use of a screen when the truck dumps the septage into the lagoon (access ramp). For financial reasons, the second option is preferred.

If a receiving station is preferred, it should include:

a) a dumping station: a covered pit with a coarse screen and hose connection;
b) a mechanically cleaned screen with an optional drained screw conveyor; and
c) a grit removal system (optional).

<u>Anaerobic lagoon</u>

The lagoon is designed to have the following characteristics:

- Its inlet (dumping zone) is equipped with a grit removal basket.

- It acts as a settling tank in which 90% or more of the TSS content is removed - sludge accumulates for 2 or 3 years, after which it is bottom pumped and irrigated over on grass forage land.

- It provides 50% or more reduction of BOD_5, 20% removal of TN and 35% removal of TP (to be verified).

- It contains a floating fat layer to be removed manually (accumulation in a corner due to wind shear) or mechanically (skimmer). This layer might even provide advantages for the treatment: it reduces odor emission (H_2S, volatile fatty acids), ensures that the lagoon is completely anaerobic and functions as a heat insulator.

TSS removal

TSS removal is achieved by quiescent settling. Appendix A contains the summary of the settling tests conducted on the septage wastewater: 90% removal is achieved within 72 hours. After this time, in a 2.32 m column of liquid, the supernatant zone is 1.72 m and the thickened/sludge zone is 0.60 m. A 3.90m deep anaerobic lagoon is required, including a 0.3m freeboard. This also includes 1.20m for sludge accumulation to be removed by pumping and irrigation. Approximately 0.7m is attributed to precipitation accumulation in the fall, winter and spring. Intrusion of groundwater must be prevented through the use of a clay liner.

BOD_5 removal

BOD_5 removal is achieved in two ways :

1) By settling of suspended solids. Digestion gas may re-suspend some material.
2) By anaerobic digestion of soluble organic matter associated with the deposition of biomass and the release of carbon dioxide and methane.

Tchobanoglous & Burton (1991) reported BOD_5 conversion rates of 50% to 85% at a detention time of 20 to 50 days and a temperature range of 6 to 50^0C. With BOD_5 loading rates between 22 to 560 kg/ha/day and an operational depth of 2.4 to 4.8 m, the effluent suspended solids concentration is 80-160 mg/l. Removal rates of 92% were reported by the EPA (1984) for a septage lagoon in Acton, Massachusetts. The EPA specifies that the detention time should be at least 20 days. For a loading rate of 0.84 kg VS/day/1000 m^2 and 500 days of detention time, the reduction should be more than 95%.

The proposed anaerobic lagoon was designed for 240 days of storage (890 m^3) from October 6th till May 31st. In addition, a 0.3m freeboard and 0.7m for precipitation (wet winter, 10 year return period) are added. At the end of the treatment period, the lagoon only contains the accumulated sludge. Thus, some elements of septage will be stored for 240 days, others 0 days. Assuming complete mixing, the average detention time is 120 days for fall and winter storage. Between June 1st and October 5th, 460 m^3 of new septage is to be added. During this period, the entire content (1350 m^3) will be transferred to the facultative pond at the average daily rate of 10.8 m^3/day. Note that the mean evaporation (0.65 m) during this period approximately compensates for the precipitation accumulated in the anaerobic lagoon in winter (0.7m).

The overall performance of the pond can only be extrapolated from other comparable sites. The BOD_5 removal was estimated as 50% because limited digestion occurs in winter. The effluent concentration is estimated to be 3,500 mg/l.

Phosphorus and nitrogen removal

The total phosphorus reduction is taken as a direct proportion of the TSS removal. The effluent concentration is estimated to be 33 mg/l. To be conservative, the TKN removal is considered to be 20%. The effluent concentration is estimated at 560 mg/l.

Dimension of the anaerobic lagoon

a) Total depth: 3.6 m + 0.3 m freeboard = 3.9 m

b) Useful storage depth = 3.9 m - 1.2 m accumulated sludge - 0.7 m precipitation - 0.3 m freeboard = 1.7m

c) Surface area A_{AN} at water level assuming straight banks is:
A_{AN} = 890 m^3 / 1.7 m = 523.5 m^2 or 37.5 m x 14 m

All the dimensions have to be adjusted to the side slope requirements.

Facultative pond

BOD$_5$ removal

In Embrun, Ontario, Weil *et al*. (1997) measured a 91.5% reduction in BOD$_5$ with a 150 kg/ha/day loading rate into a facultative pond. The mean influent and effluent BOD$_5$ were 2567 mg/l and 215 mg/l respectively (detention time: 275 days). Kinetic removal rates under local climatic condition have yet to be computed. In the Grand Bend design, a conservative approach is to assume that the loading encountered in Embrun will produce an 80% removal in BOD$_5$. Thus, the effluent concentration in BOD$_5$ would be approximately 725 mg/l.

The mass loading M_F and required treatment area A_F are:

$$M_F = 10.8 \text{ m}^3\text{/day x } 3500 \text{ mg/l x } 10^{-3} = 37.8 \text{ kg/day}$$

$$A_F = 37.8 \text{ kg per day / } 150 \text{ kg per ha per day} = 0.252 \text{ ha} = 2520 \text{ m}^2$$

The dimensions are:

length = 72 m
width = 35 m
depth = 1.5 m (operational level)

There is a risk however of the facultative pond becoming mostly anaerobic, due to the high requirement in dissolved oxygen. Dividing the facultative pond into two cells in series, each equipped with a wind aerator, will be considered in the detailed design. Wind aerators will be added on a per need basis.

TKN removal

In Embrun, Weil *et al*. (1997) measured a TKN removal of 88.5% for a facultative pond with a mass loading of 9.7 kg/day. The mass loading expected for Grand Bend is:

$$M_F = 10.8 \text{ m}^3\text{/d x } 560 \text{ mg/l x } 10^{-3} = 6.04 \text{ kg/day}$$

Because the expected influent BOD$_5$ concentration is high (3500 mg/l), nitrification might be limited due to a lack of oxygen. TKN removal will mostly occur by deposition of biomass and is not expected to exceed 50%, yielding an effluent with a TKN concentration between 250 mg/l and 300 mg/l. Again, dividing the facultative pond into two aerated cells would enhance the performance of the system.

Polishing low rate aerobic pond/marsh area

The polishing low rate aerobic pond/marsh is designed to aerate the waste to minimise odour problems as well as to protect against peak loading periods. A 75% reduction in BOD_5 was observed in Embrun for a 9 kg/ha/day loading rate. Some of the remaining BOD_5 is due to algae. However, the initial influent average concentration was lower than 168 mg/l in Embrun and greater percent reduction would be expected with the higher initial concentration of 725 mg/l. Tchobanoglous & Burton (1991) specify that a low rate aerobic pond is 0.9m deep, functions better at 20^0C (summer condition in Ottawa), and can be loaded between 70 and 140 kg/ha/day. It is expected that concentrations in the effluent will be the following: algae concentration of 40 to 100 mg/l, TSS of 80 to 140 mg/l and BOD_5 conversion of 80% to 95%.

The mass loading over the low rate aerobic pond is:

$$M_{AR} = 10.8\ m^3/day \times 725\ mg/l \times 10^{-3} = 11.39\ kg/day$$

The allowable loading rate is selected at a conservative 45 kg/ha/day, taking into consideration that average temperatures in May and September are much lower than 20^0C. Thus, the required treatment area is:

$$A_{AR} = 11.34\ kg / 45\ kg/ha/day = 0.1740\ ha = 1740\ m^2$$

Dimensions: Length= 50 m Width= 35 m

The depth is 0.9 m in the first half of the pond/marsh (23.5 m) and 0.45 m in the second half (23.5 m).

The marsh section (second half) is deeper than the usual 0.2m to promote aerobic conditions, as anaerobic conditions would cause odours. This approach will also reduce the algae production. The shallower area of the pond will be rapidly colonized by cattails, which will further aerate the bottom sludge. The expected BOD_5 concentration is approximately 60 mg/l to 260 mg/l. The expected TKN concentration based on observation in Embrun is approximately 60% to 70% of the influent concentration, thus between 160 and 220 mg/l or an average of 190 mg/l.

Irrigated area

The effluent yearly mass loading into the irrigated area is:

M_{IR} $= 1350\ m^3 \times 190\ mg/l \times 10^{-3} = 256.5\ kg$

Based on the crop requirements, the filter area required will be approximately:

A_{IR} $= 256.5\ kg / 140 kg/ha = 1.83\ ha$

The land application proposed is by gravity along a pipe set at the crest of two sloped beds:

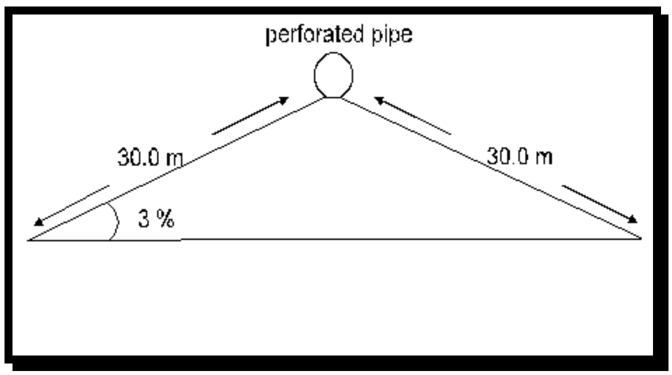


Figure 1: Sloped bed design

- Width of each bed: 60 m
- Length of each bed: 150 m
- Crop suggested: a grass forage crop is suggested initially. This grass forage is not to be consumed by animals. The few bales harvested are to be composted. A poplar or pine plantation would ensure an efficient and beneficial long term disposal of the effluent. The requirements for nitrogen and phosphorus are approximately the same for trees as for grass forage and corn.

Summary

The dimensions of the proposed treatment system are summarized in the following table:

Table 4: Septage treatment system design

	L (m)	l (m)	V (m^3)	D (m)	dt (day)	BOD_5 (mg/l)	TKN (mg/l)
Anaerobic Lagoon			890[1]	3.9[2]	240	3500	560
Facultative pond	72	35	3780	1.5[3]	350	725	250-300
Aerobic pond / Marsh	50	35	1180	0.9 0.45	73 36	60-260	160-220

[1], [2], This is the useful storage volume required. The 3.9 m total depth includes 0.3 m for freeboard, 1.2 m for accumulated sludge and 0.7 m for precipitation. A clear 890 m^3 must be available. [3] Operational level

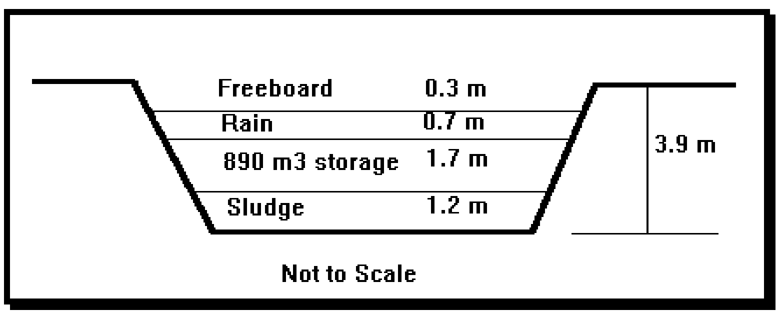


Figure 2: profile of the lagoon

- The total volume of soil excavated/placed is about 8000 m^3.
- The transfers could be done by gravity, but pumps allow better control. For that reason, a pump is recommended between the anaerobic lagoon and the facultative pond.
- Two crowned beds 60 m x 150 m follow the marsh. Initially, the crop would be grass forage. It cannot be consumed (it is only a few bales). Christmas trees or poplars are recommended for the long term.
- The sludge at the bottom of the anaerobic pond can be pumped every two to three years. If it is irrigated in the fall, the forage can be used the following spring.
- The total system should cost about $40 000, plus the cost of any clay liner, plus engineering.
- Figures 3 and 4 represent the layout of the treatment system.

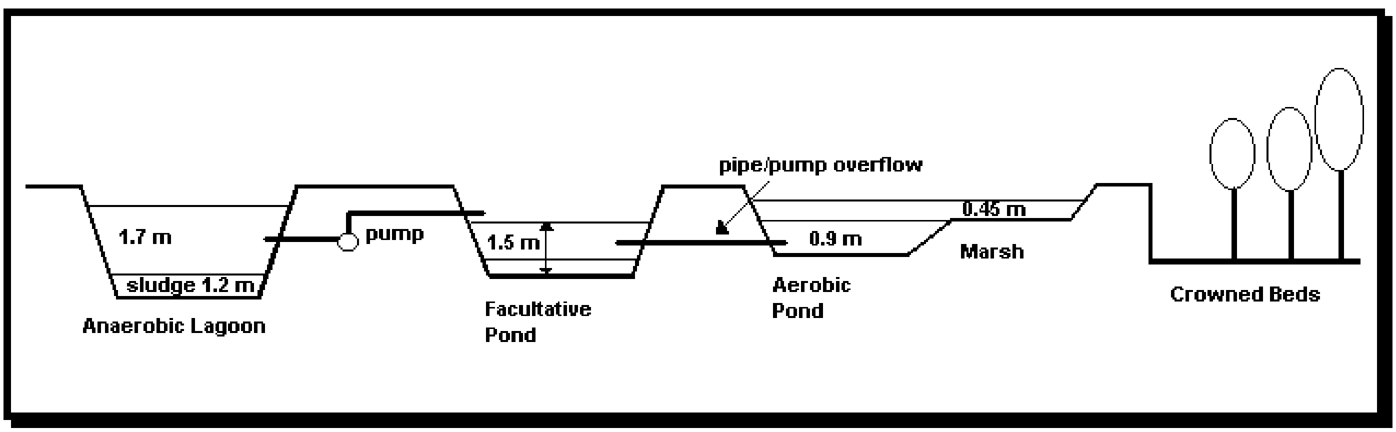


Figure 3: Cross Section of Septage Treatment System

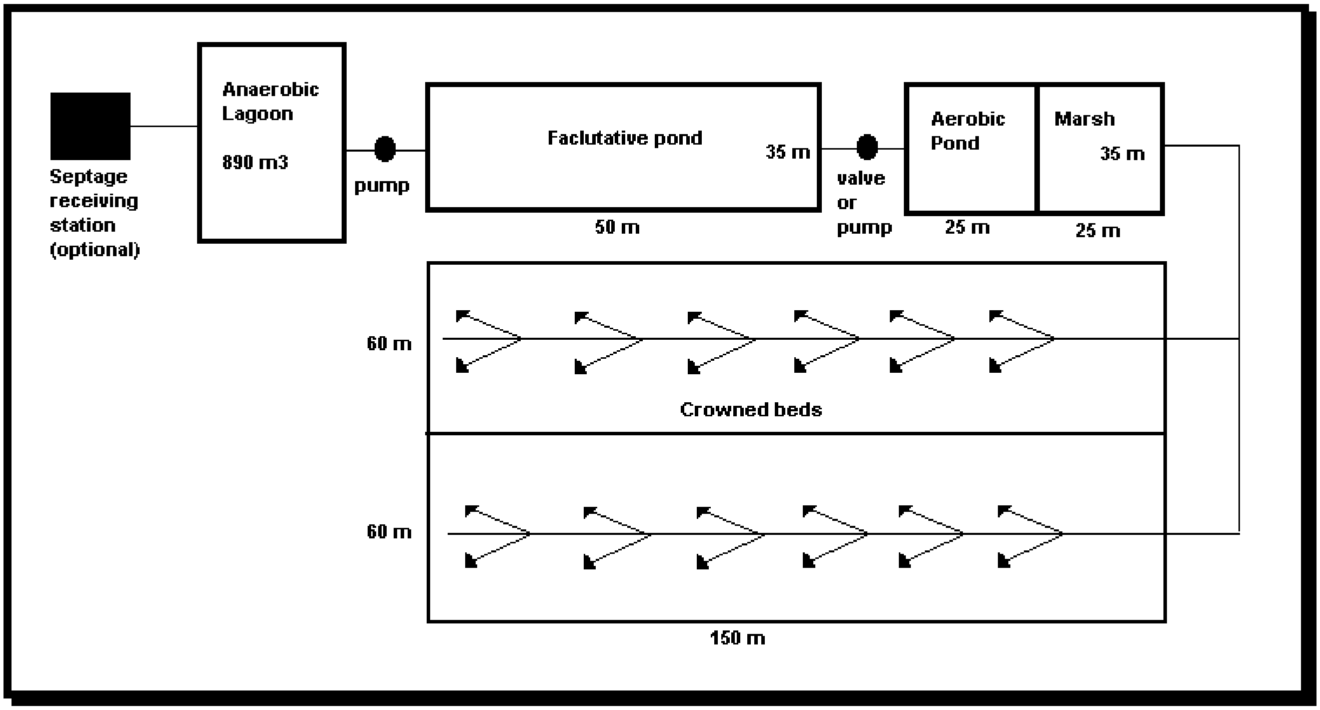


Figure 4: Plan View of septage Treatment System

CONCLUSION

Septage has high pollutant concentrations. It is usually land applied or treated in wastewater treatment plants. However, due to subsidy cuts and public pressure, it will be more and more difficult to use these conventional systems. New independant treatment systems are likely to appear to solve these problems. However, these are often labour intensive, expensive, or present a threat to the environment.

A new system to treat septage is proposed. It includes a pre-treatment, an anaerobic lagoon, a facultative pond, an aerobic pond, a marsh and an irrigation area. This system is simple and improves traditional anaerobic lagoons by reducing the risk of pollution of groundwater. Its cost is also much lower than that of traditional treatment processes. Finally, with the increasing cost to dispose of septage in wastewater treatment plants and the higher difficulty to apply it to land, this new septage treatment system should provide an alternative for the septage industry. In the long term, it will also reduce the costs for the people who generate septage.

APPENDIX F

FOOD PROCESSING WASTE TREATMENT

USING CONSTRUCTED WETLANDS

CONSTRUCTED WETLANDS, REED BEDS AND OVERLAND FLOW FOR THE TREATMENT OF FOOD PROCESSING WASTWATER

(by: Michael H. Ogden, P.E., The Southwest Wetlands Group Inc., Santa Fe, New Mexico, USA)

INTRODUCTION

Wastewater from food processing facilities are generally characterized by high BOD/COD and high suspended solids. In some industries, the high BOC/COD numbers are the result of high concentration of fats, oils and grease. On occasion the Southwest Wetlands Group has seen COD's over 40,000 mg/l from an egg processing facility. In addition, nutrients may be out of balance; i.e. the ration of C:N:P does not match the normally occurring ratios in the bacteria that are essential for treatment. Finally, the micronutrients for microbial growth are often also lacking.

DESIGN CONSIDERATIONS

Reed Beds and constructed wetlands generally require some from of pre-treatment. The appropriate from of pre-treatment will depend on an analysis of the wastewater. Wastewater should be analyzed for BOD, COD, C, N, P, S, fats, oils, grease and settling characteristics. Some food processing wastewater such as eggs and dairy contain colloidal solids that are very difficult to remove by settling. Primary treatment options include the following:

- Settling tanks,
- anaerobic tanks (septic tanks - settling and anaerobic digestion),
- dissolved air floatation (removal of fats, oils, grease and colloidal solids),
- high rate bio-filtration (packed media in vertical flow enclosures),
- equalization/mixing tanks (pH adjustment).

Pre-treatment using mechanical aeration systems can also be considered, but because of energy considerations, this form of treatment is usually not recommended. Fats, oils and greases (FOG's) when separated can be sent to a rendering factory, or treated on-site. FOG's require aerobic treatment at elevated temperatures; however, once the levels have been reduced to 140 mg/l or less, reed beds and constructed wetlands can successfully treat FOG's.

Figure 1 represents a typical project showing the various components for the treatment of a high nitrogen (N>300 mg/l) and high COD (occasionally exceeding 40,000 mg/l) wastewater stream. In this layout, the reed bed can be operated serially or in parallel. This particular layout can be considered as a general solution to the problem, but it must be stressed, that since food processing operations are very different from industry to industry, and plant to plant, the designer must pay particular attention to the wastewater stream, including daily and seasonal fluctuations as well as all of the items listed above. The requirements for nutrient and microbial additions must also be assessed.

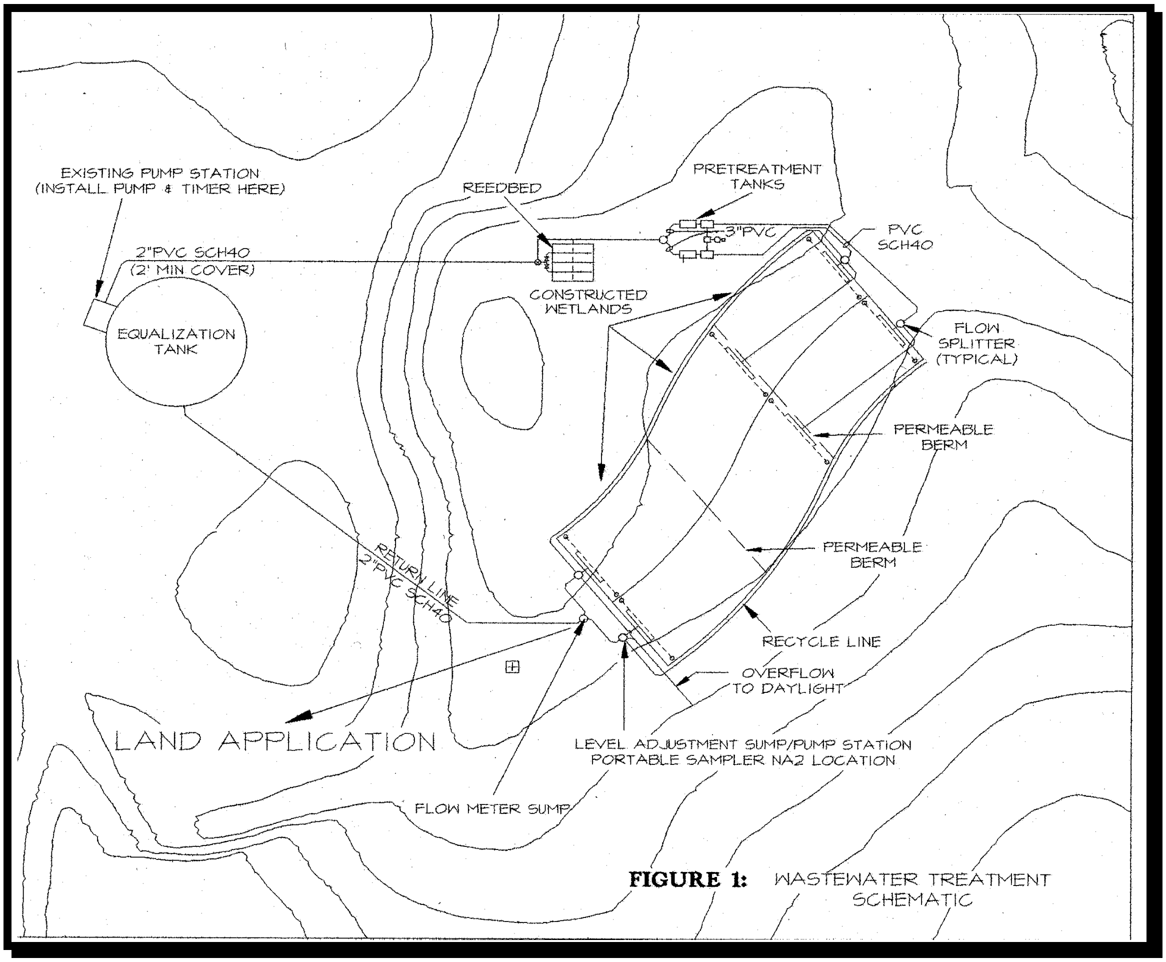
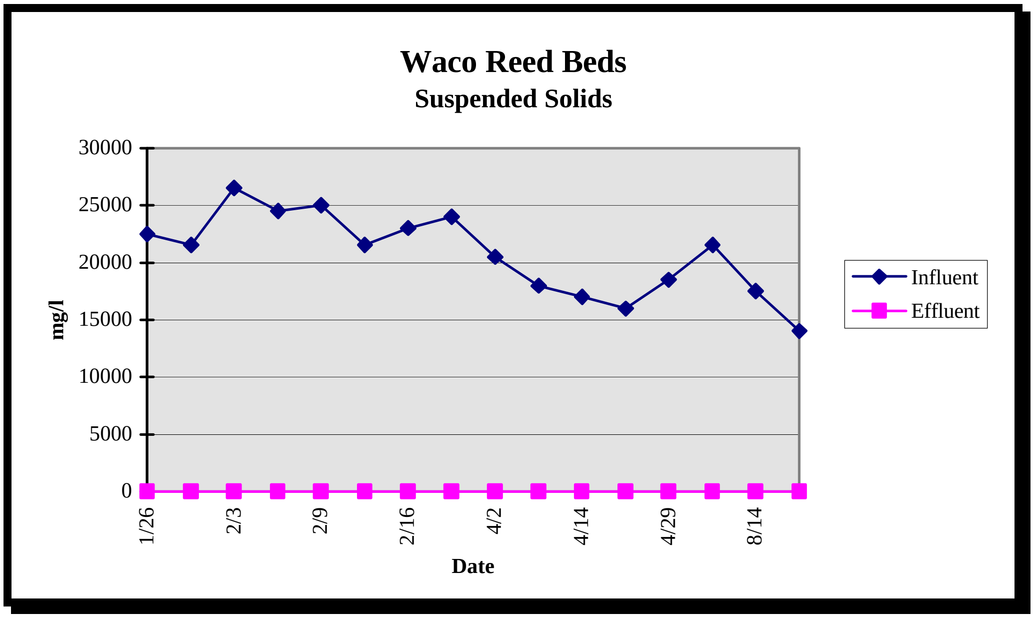


Figure 1 - Wastewater Treatment Schematic

Once primary treatment has been accomplished, reed beds and constructed wetlands are used in parallel or series. If colloidal solids are present, then the use of reed beds and wetlands in series can reduce the colloids to acceptable levels. If solids levels are high, and primary treatment has produced sludge, then the reed bed can be placed as a parallel operation with supernatant from the primary treatment going to the constructed wetlands and sludge going to the reed bed.

Reed beds are excellent for the removal of solids. Figure 2 represents the sludge removal from a reed bed at a candy factory.

Figure 2 - Removal Rates, Solids



Sludge from primary treatment can be introduced directly onto the reed beds. Sludge concentrations from 0.5% to 4.0+% can be applied throughout the year. Some additional BOD/COD removal will take place, but this should not be counted on for treatment. The rate of application depends on the level of pre-treatment and the nature of the primary sludge.

Application rates from 40 kg/m^2/yr to 160 kg/m^2/yr have been used. Higher rates are appropriate for aerobically stabilized sludge, or in the case of anaerobic sludge where odors are not a major consideration. At the lower loading rates, raw sludge can be applied without significant odor problems from most food processing wastewater. Usually odor is present only during the loading cycle which is of a very short duration.

Reed beds are an excellent means of dewatering sludge, and are designed to allow the sludge to accumulate over a period of 7 to 10 years. Use of reed beds eliminate the need for mechanical presses, further digestion, and provides a stabilized sludge suitable for land application. Because of the action of the stems and roots as well as the associated microorganisms, the sludge is exposed to oxygen and subsequently oxidized.

Water from the reed beds is collected in under drains, and is then directed to constructed wetlands. Constructed wetlands can be either surface flow or subsurface flow, or combination thereof. Surface flow wetlands have lower reaction rate constants than subsurface flow wetlands. They are however less expensive to build, and because of exposure to wind, the ability of surface flow wetlands to oxidize carbon compounds is greater. Subsurface wetlands are anaerobic or anoxic, and rely more on methane production for the removal of carbon. Both types of wetlands are excellent for denitrification. Nitrification is problematic and seasonally dependent.

Cold weather operations are accommodated by acknowledging that the microbial process are temperature dependent. To accomplish treatment, the designer must design for the worst case conditions, i.e. January. Surface flow wetlands generally form ice covers in extreme climates with treatment continuing under the ice. Surface flow wetlands are successfully operating in Mandan, North Dakota, and subsurface wetlands north of the Arctic Circle in Norway. Seasonal operations are an alternative.

Wetlands designs are based on real loading formulas. There are limits to the amount of solids that can be introduced into the wetlands without suffocating the roots of the plants. Uniform distribution of solids is an important design consideration. However, if BOD/COD loadings are introduced in soluble form it is possible to continuously introduce wastewater into wetlands cells with BOD concentrations in excess of 4000 mg/l, provided of course that the designer is paying particular attention to nutrient balances.

If reed beds and constructed wetlands are used to reduce BOD/COD concentrations, then land application is an excellent option for the final disposal of the treated effluent. As Figures 3 and 4 demonstrate, land application can have a significant impact on the final treatment. The amount of land required will depend on the nature of the discharge permit. It may be possible to totally retain all effluent on site, or it might be necessary to discharge the final effluent into an adjacent stream.

SUMMARY

The design strategy must include all of the various constituents of the wastewater stream, including the absence or relative deficiency of nutrients. Exposure of the wastewater stream to various different environments can enhance the treatment process. Multiple ecologies such as ponds, marsh, meadow allow a range of microbial communities to take advantage of the nutrients and carbon in the wastewater stream. Strategies can include the arrangements as presented in Figure 5. These examples can be varied by selecting multiple ecologies, adding recirculation, and by changing the plant species to reflect nutrient requirements.

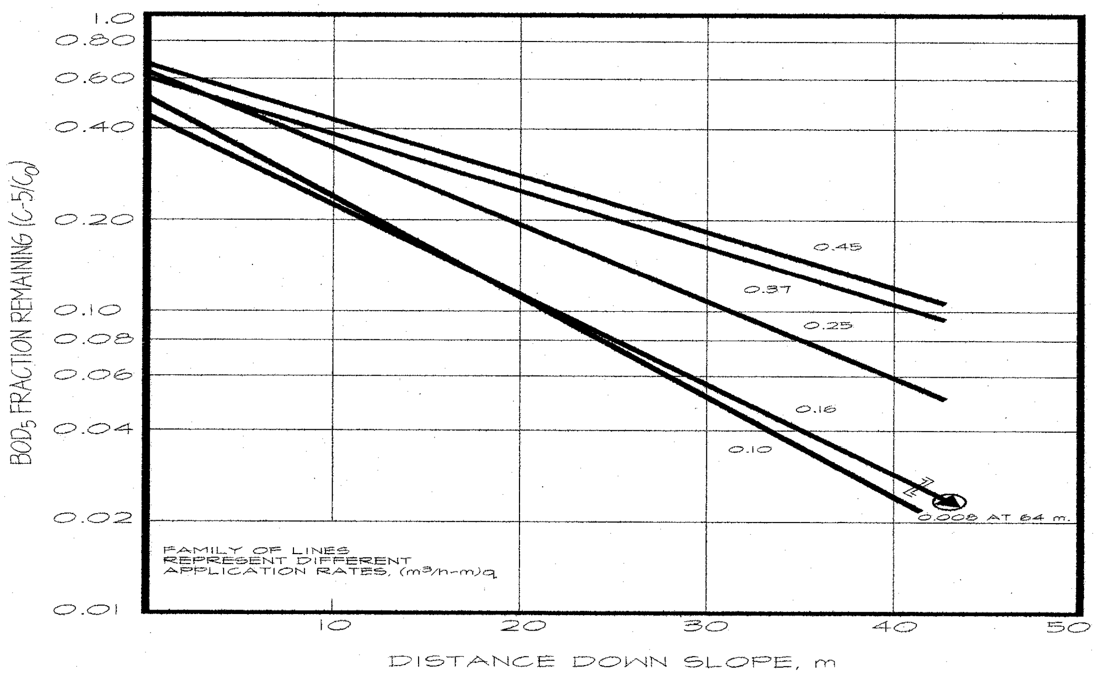


FIGURE 3

BOD_5 FRACTION REMAINING VS. DISTANCE DOWN SLOPE WITH SCREENED RAW WASTEWATER (4)

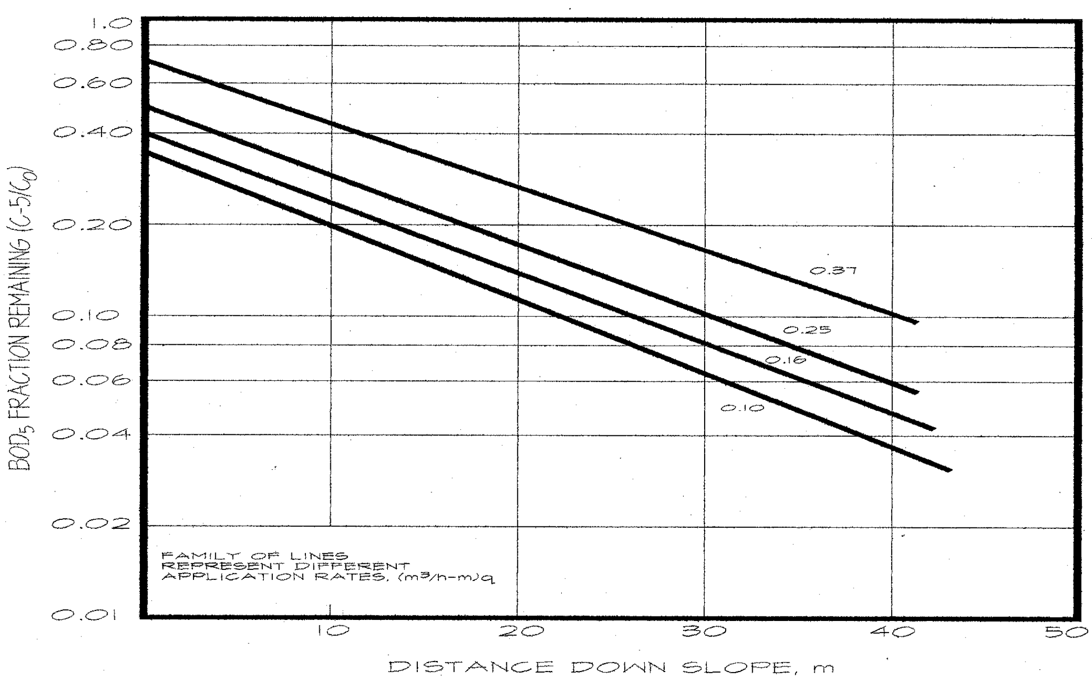
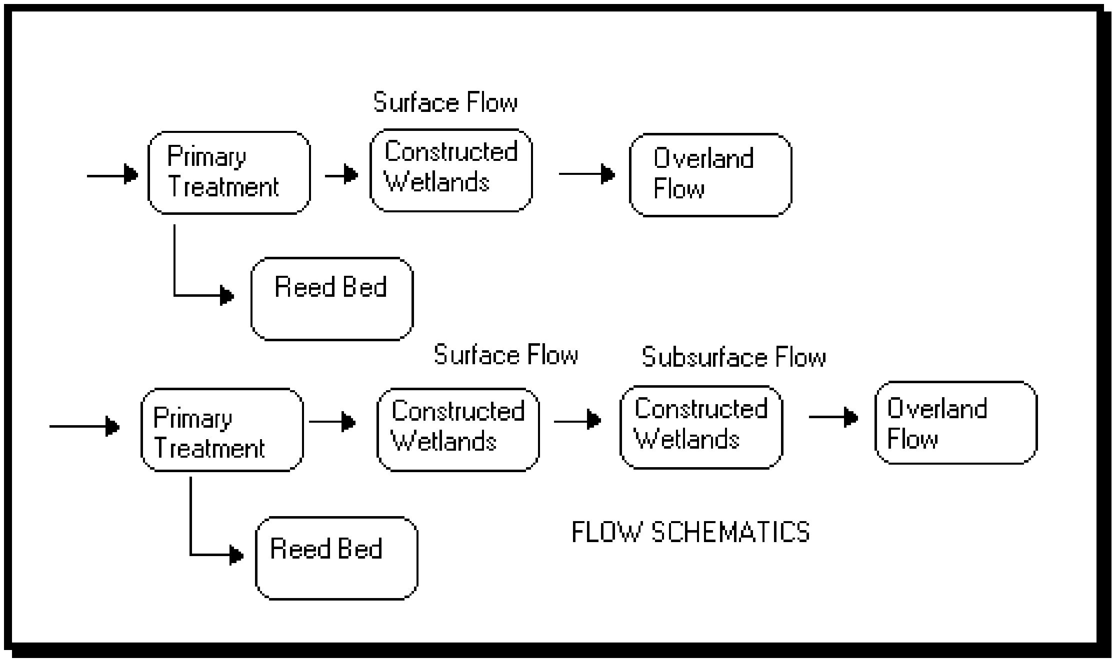


FIGURE 4

BOD_5 FRACTION REMAINING VS. DISTANCE DOWN SLOPE WITH PRIMARY EFFLUENT (4)

FIGURE 5
FLOW SCHEMATIC



REFERENCES

- Reed, S.C., Crites, R.W. Middlebrooks, E.J., *Natural Systems for Waste Management and Treatment, 2nd edition.* McGraw-Hill Inc, New York, 1995.

- Hammer, D.A., ed. *Constructed Wetlands for Wastewater Treatment; Municipal, Industrial and Agricultural.* Lewis Publishers, Chelsea, MI, 1989.

- Reed, S., et al. *Process Design Maul; Land Treatment of Municipal Wastewaters*. USEPA 625/1-81-013. Center for Environmental Research, Cincinnati, OH, 45268.

- Kim, B.J., *Performance Evaluation of Existing Reed Beds for Sludge Dewatering*. Water Environment Federation, Alexandria, VA, Oct, 1993.

- Nielsen, S.M. *Biological Sludge Drying in Constructed Wetlands. Pub. In "Constructed Wetlands for Water Quality Improvements"*. Lewis Publishers, Chelsea, MI, 1993.