HORIZONTAL SUBSURFACE FLOW CONSTRUCTED WETLANDS FOR ON-SITE WASTEWATER TREATMENT

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TABLE OF CONTENTS

FIGURES

TABLES

LIST OF ABBREVIATIONS

BOD	biological oxygen demand
CW	constructed wetland
EPA	Environmental Protective Agency
HWTS	home wastewater treatment system
N	nitrogen
NPDES	National Pollution Discharge Elimination Systems
OAC	Ohio Administrative Code
OEPA	Ohio Environmental Protection Agency
ORC	Ohio Revised Code
P	phosphorus
PE	population equivalent
SSFCW	subsurface flow constructed wetland
STS	sewage treatment system
TI	title search
TMDL	Total Maximum Daily Load
TS	topic search
TSS	total suspended solids
USEPA	United States Environmental Protection Agency

ABSTRACT

Horizontal subsurface flow constructed wetlands (SSFCWs) are being used worldwide to treat wastewater from a variety of sources. An extensive literature review was conducted to update the current state of scientific knowledge on the performance of SSFCWs for domestic wastewater treatment. This review documented good treatment efficiency for the five commonly measured parameters (TSS, BOD, nitrogen, phosphorus, and fecal coliforms).

An attempt at a Meta analysis turned up a myriad of problems preventing a proper statistical review. These include lack of adherence to standard methods for effluent analysis, varying metrics for reporting treatment efficiency, variability in the nitrogen species which is measured, lack of uniformity of design of the wetlands and on-site systems, and variation in standards required by various agencies and countries. It was not possible to do a Meta-analysis to prove that SSFCWs should be approved technology for onsite wastewater treatment in Ohio.

The author recommends that SSFCWs be approved in Ohio for secondary treatment of home wastewater prior to final treatment by small soil absorption systems. The author recommends that SSFCWs be approved for replacement of failing systems in situations with a high water table or poor soils. A number of other areas need further consideration or research. Ohio Department of Health should serve as a repository for a state-wide database of SSFCWs. USEPA and OEPA should set discharge standards as mass loading based on the volume of effluent discharge, with minimally discharging systems allowed a higher concentration of pollutants than large volume dischargers. USEPA should define what is meant by “failure”. Research should be funded to determine the treatment results when iron is used in a SSFCW, to find the ideal design for SSFCWs to assure non-discharge when used for secondary treatment, and to determine the most efficient, economical design for technology export to developing

countries. The author recommends that the critical nitrogen species measured should be ammonia **N.**

INTRODUCTION

The Importance of Efficient Wastewater Treatment

Efficient wastewater treatment is critical for the world. There is unprecedented environmental pressure being exerted on the environment by the rapidly expanding population. This growing population requires adequate clean groundwater to drink. The environment demands relatively unpolluted surface water in streams and lakes to maintain the flora and fauna that humans have come to rely upon for food and recreation.

Moeller estimates that 80% of the total disease burden in developing countries comes from waterborne illness. “Diarrhea still claims an estimated 2,000,000 children a year” ("Moeller, 2005). China reports that 300,000,000 of its citizens lack safe drinking water (Kurtenbach, 2005). In the USA, 95% of the population in rural areas receives its’ drinking water from groundwater-recharged wells (US Environmental Protection Agency, 1998). Water purification is the ultimate technique to ensure safe drinking water. However, in most individual home systems in America, and in much of the supply in developing countries, water is untreated. The polishing of sewage to release safe effluent (or no effluent) is thus an important environmental health commitment.

Recent surveys indicate that failing septic systems are the third most frequently cited source of groundwater contamination in the United States (US Environmental Protection Agency, 1998). USEPA also estimates that on-site septic systems serve approximately 25% of the US population (US Environmental Protection Agency, 1997). Data from Minnesota show that 30% of residents rely upon on-site systems, and over 50% of these are estimated to be out of compliance with state standards or are hydraulically failing (Axler, Henneck, & McCarthy, 2001). Although no state-wide data are available for Ohio, personal surveys of Health

Commissioners indicate failure rates are comparable, more than 10% in Logan County in 2005 (Boyd Hoddinott, Health Commissioner). An even higher percent of mechanical aerobic systems are failing in southwest Ohio (personal communication, Jim Luken, Miami County Health Commissioner). In Lithuania, one third of aeration systems are failing (Gasiunas, Strusevicius, & Struseviciene, 2005). The USEPA also estimates that one quarter of soil in the US is unsuitable for drain field use (U.S. Environmental Protection Agency, 1980). It seems obvious in light of all the above data that there is a problem with on-site sewage treatment.

The author could not find a definition of an ideal home sewage treatment system. Based on the literature search, discussions with workers in the field, and his own experience, the author proposes that an ideal system would meet the criteria set out hereafter.

i) It must not discharge to the ground, ditch, or stream.

ii) It must treat sewage to meet EPA standards if it does discharge.

iii) It must be energy independent and not use mechanical devices, except a pump designed to lift the sewage from the home to a higher elevation no more than once daily.

iv) It should be simple and relatively inexpensive to build.

v) It must be easily understood by the homeowner.

vi) It must be simple and relatively inexpensive to maintain. This means pumping the tank once every five years, switching a valve between treatment devices no more than once a year, and changing pumps no more than once every 15 years.

vii) It should be unaffected by soil type.

viii) It should be functional in the presence of a high water table.

ix) It should last the life of the house. It should have a replacement area in case of failure.

x) It should have a small footprint on a one-acre lot

There is no affordable system that can meet all of the above criteria. After seeing first hand the performance of seven “experimental” subsurface flow constructed wetlands in Logan County, the author was stimulated to investigate the current status of research on SSFCWs.

Wetlands

Wetlands are areas where water covers the soil or is present near the surface for most of the year. Saturation with water is the dominant factor that determines the types of plant and animal species that live on and in the water and soil, and in fact, determines the eventual make-up of the soil in wetlands. Traditionally, areas considered as wetlands would be swamps, marshes, and bogs. With the increased knowledge over the past decades of the importance of wetlands in nature’s life cycle, *created wetlands* are being developed from non-wetland sites to produce or replace natural wetlands.

Constructed wetlands (CWs) are wetlands intentionally created from non-wetland sites for the sole purpose of wastewater or storm water treatment. Such systems are being used worldwide to treat just about any wastewater imaginable, including that from mines, animal and fish farms, highway runoff, industry of all types, and municipal and domestic sewage (Mitsch & Gosselink, 2000; Various, 7th International Conference on Wetland systems, 2001; J. Vymazal, 2002).

Constructed wetlands have been classified according to the life form of the dominant macrophyte (plant) in the wetland into: (i) *free-floating macrophyte-based systems*, (ii) *emergent macrophyte-based systems*, and (iii) *submerged macrophyte-based systems* (H. Brix, 1994). Emergent macrophyte-based systems can be further classified into *free water surface flow*, *subsurface horizontal flow*, and *vertical (nonsaturated) flow*. In horizontal subsurface flow constructed wetlands (SSFCWs), the water level is maintained below the surface of the medium used in the beds, and thus no sewage is exposed to the surface to present potential risk to humans or to cause odor or insect infestation. The active reaction zone of constructed wetlands is the root zone (or rhizosphere). The main function of the macrophyte is to serve as a habitat for attachment of microorganisms. Purification of wastewater in SSFCW is based on the interaction of plants, microorganisms, the soil medium, and pollutants in a complex system of physical, chemical, and biological processes that are not yet fully understood. Many of these will be discussed in this paper.

Standards Guidelines

SSFCWs that discharge treated domestic wastewater to surface water must meet United States National Pollution Discharge Elimination Systems (NPDES) permitting guidelines in order to be in compliance with pollution reduction goals implemented under the watershed Total Maximum Daily Loads (TMDL) program (US Environmental Protection Agency, 2001b). The Ohio Environmental Protection Agency has mandated even stricter effluent concentration standards, and discourages any off-lot discharge (Ohio Environmental Protection Agency, 1999a). There is no economically priced home wastewater treatment system that can meet the rigid OEPA standards for discharge of nitrogen (1.5 mg/l) and phosphorus (1 mg/l). It is reasonable to prefer, based on these standards that on-site systems not discharge. As documented above however, the reality is that significant percentages (25-50 %) of tile bed and aerobic systems do fail and subsequently discharge onto land and into surface and ground water.

The monitoring of the EPA guidelines for semi-public disposal systems may be delegated to local health departments through blanket authority and oversight from the EPA (ORC 3709.085). Many departments in Ohio lack the manpower and expertise (soil specialists) to administer this program properly. In Ohio, constructed wetlands are still considered "experimental" and require approval from the Director of Health before they can be used in on-site systems. This approval process has discouraged developers, homeowners, septic contractors, and the local health departments responsible for licensing on-site treatment from using this technology. After almost 30 years of outdated sewage legislation, a new law was signed by the governor of Ohio in 2005. Rules are currently being written for that law under OAC 3701-29, with target adoption slated for December 2006. That makes this the ideal time for reconsideration of the permitting process for SSFCWs.

PURPOSE STATEMENT

The purpose of this paper is to assess the current state of subsurface flow constructed wetland technology for home wastewater treatment through a comprehensive literature review.

The second purpose is to determine through rigorous scientific assessment whether SSFCWs can meet or exceed current standards set for home systems in Ohio. This will be done through a Meta-analytic procedure.

The over-arching goal of any such study is to improve public policy. If it can be proven that SSFCWs are capable of matching or exceeding conventional systems (soil absorption devices) in some circumstances, then the author will advocate for their acceptance in those situations.

LITERATURE REVIEW

In 1953, Dr. Kathe Seidel first discussed the possible use of wetlands “to lessen the over fertilization, pollution and silting up of inland waters through appropriate plants so allowing the contaminated waters to be capable of supporting life once more” (Seidel, Happel, & Grau, 1978). The Tennessee Valley Authority was one of the US pioneers in the use of wetlands during the 1980s. The first full technology assessment was published by the USEPA in 1993 (US Environmental Protection Agency, 1993). This also outlined topics needing further investigation. Hans Brix, one of the researchers who brought this technology to the forefront, authored a 1994 article that presented a large world-wide database of results that showed impressive wastewater treatment by subsurface flow wetlands (H. Brix, 1994).

Eight years later, Jan Vymazal published a summary of ten years experience in the use of constructed wetlands (CWs) for wastewater treatment in the Czech Republic (J. Vymazal, 2002). His summary is an excellent starting point for a literature review of recent research on the design, mechanics, and performance of CWs. Although many of the systems built by the Czechs are designed for the treatment of large sewage flows (500-1100 population equivalents, PE), Vymazal’s huge database dwarfs that of any other recent authors and is particularly pertinent to similar cold weather climates such as Ohio’s.

Vymazal states that there are over 100 CWs in the Czech Republic, but in his treatment results, he has included 38 systems for which he has relatively complete data. All of these are horizontal subsurface flow constructed wetlands treating municipal or domestic wastewater. He admits that his data is somewhat limited by Czech legislation that only allows the monitoring of discharged water quality. That legislation requires standards only for suspended solids (SS) and biological oxygen demand (BOD_5) parameters for sources of pollution from less than 500 PE.

As a consequence, data from non-discharging systems was included only when homeowners requested studies, or when the system was large, publicly owned, and treating sewage from more than 500 PE. This introduces bias into his statistics, and necessitates comparison with other studies on CWs. Vymazal presents results from several other countries and continents. He does not say how he compiled that database. The percentage of on-site systems that did not discharge would have been an important statistic to include. If the system does not discharge effluent into the environment, the treatment results are obviously only important for research purposes. Another problem with his database is that many of the CWs are much larger than single domestic systems, but the data is not divided to show results from smaller systems.

Horizontal Subsurface Flow Constructed Wetlands

1. Design parameters

A) Pretreatment

Subsurface flow constructed wetlands (SSFCWs) are primarily designed for secondary or tertiary treatment of wastewater, and use a septic tank pre-treatment stage similar to most home systems. This very critical first step removes most solids (measured as Total Suspended Solids, TSS), which settle to the bottom and are degraded by anaerobic bacteria. Maintenance of a septic tank is simple; a regular cycle of pumping is all that is necessary after proper initial installation. Ohio State Extension gives a chart of expected pumping frequencies (Ohio State University Extension). Neglecting regular pumping is one of the most important causes of failure of properly designed and situated on-site systems. Clogging of the inlet to the wetland (or the tile bed, mound or aeration bed) and subsequent surface flow is the result of waiting too long to pump the tank (Dahab & Surampalli, 2001; Davison, Headley, & Pratt, 2005). As Davison states, “source control of TSS by means of a well designed, installed and maintained primary treatment device is the first line of defense against entrance zone substrate clogging”. He is referring to the regularly pumped septic tank as that defense for single-family systems. In Davison’s study detailing aspects of design, structure, performance, and operation of CWs, he found that certain species of earthworms worked to prevent clogging at the inlet (Davison et al., 2005). This is a completely natural treatment that can partially substitute for owner maintenance. There is need for an experiment to find out what kinds of earthworms will perform this function best in northern climates.

B) Surface Area and Bed Configuration

Figure 1 is from Davison’s 2005 article and shows a schematic of a typical SSFCW (reed bed).

Figure 1: Schematic of Typical Reed Bed
(Davison et al., 2005)

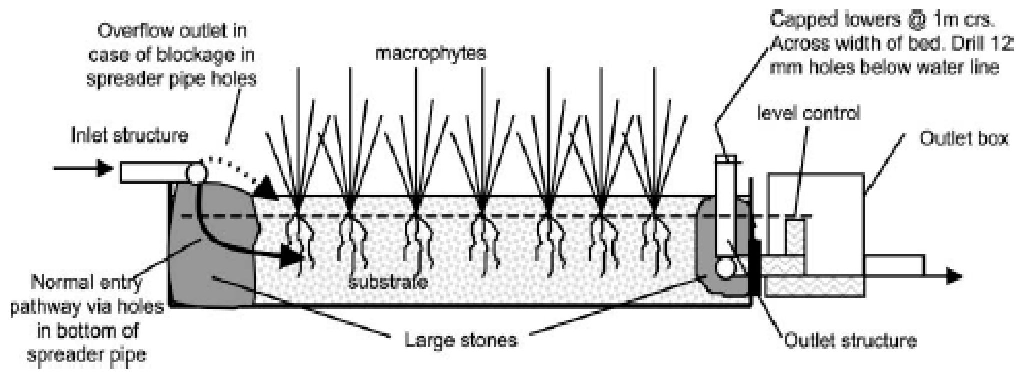
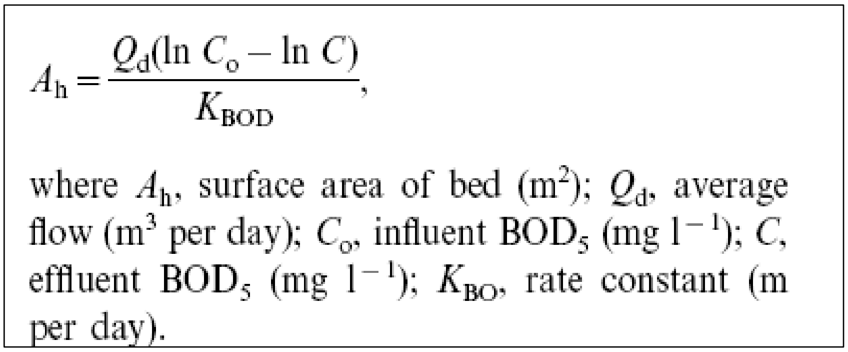


Figure 1 Elevation of typical reed bed showing major components

A simple formula to determine surface area for the wetland cells is given by Vymazal. This formula has resulted in a general “rule of thumb” for total area of cells of 5m^2 (50 ft^2) per PE. This seems small by North American Standards. City of Austin recommends 300-400 ft^2 for a typical family home (City of Austin-Onsite Treatment (Pretreatment) System

Fact Sheets, Retrieved February 3, 2006). Steer used two cells in his Ohio CW systems, each 25m^2 ($500\ \text{ft}^2$ total), about twice that used by Vymazal (D. Steer, Fraser, Boddy, & Seibert, 2002).

Figure 2: Vymazal Formula for Surface Area



$$A_{\mathrm{h}} = \frac{Q_{\mathrm{d}}(\ln C_{\mathrm{o}} - \ln C)}{K_{\mathrm{BOD}}},$$

where A_{h}, surface area of bed (m^2); Q_{d}, average flow (m^3 per day); C_{o}, influent BOD_5 ($\mathrm{mg\ l}^{-1}$); C, effluent BOD_5 ($\mathrm{mg\ l}^{-1}$); K_{BO}, rate constant (m per day).

The size of the footprint of any on-site system is obviously very important on lots that do not have adequate area or that have poor soils or a high water table. The size requirement for leaching fields comes from Ohio Administrative Code 3701-29-11, supplemented by the Ohio Department of Health Interpretive Guide from 1977. In moderately limited soils (as occur in Logan County) the linear feet of trench is 200 per bedroom. With the typical six-100 foot runs and eight feet between the two foot wide trenches, the coverage is 100 x (6x2+8x5)=5200 square feet. Most of Logan County sites require curtain drains (adding another 2000 ft^2) and have severe soils (adding a further 2500 ft^2). With the replacement, set-aside the total area needed is 23,000 ft^2 or half an acre. The same house could be served by an on-site SSFCW with two cells totaling no more than 500 square feet. Replacement can be done easily on the site, and so no replacement area need be set aside.

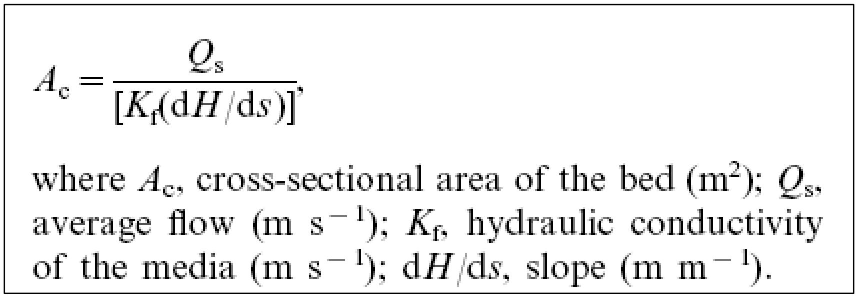
Most of the smaller Czech systems use only one bed, but those reported from other researchers use a second bed, a small tile field, or a sand filter after the first cell outflow

(Dahab & Surampalli, 2001; D. Steer et al., 2002). The first cell in these systems is always lined (see “F: Sealing the Bed”). The second cells are almost always unlined as “percolation and use of the soil column to reduce discharge from the site is deemed a positive element to the design” (D. Steer et al., 2002). In addition, the second cells may be planted with attractive ornamental plants that need not be as efficient in wastewater treatment as the first cell. Many of the wetlands in the Czech Republic do not discharge, and such non-discharge is data that has great value. Unfortunately, Vymazal does not include the number of non-discharging systems. Most of Steer’s lower flow systems do not discharge. Such data presents good reasons for designing systems with a larger surface area per PE. There is a theoretical concern of plant die-off if a wetland runs dry, but that did not happen with Steer’s systems, or with the seven non-discharging wetlands in Logan County. One of the reasons for this is the hardiness of the common reed normally used. Most authors recommend a small berm to protect the cells from water inflow from surrounding surfaces (D. Steer et al., 2002).

C) Aspect Ratio

The length to width ratio is called the aspect ratio and it is calculated from Darcy’s Law. This ratio has been considered to be of critical importance in maintaining adequate flow through the wetland.

Figure 3: Darcy’s Law for Aspect ratio



$$A_c = \frac{Q_s}{[K_f(dH/ds)]},$$

where A_c, cross-sectional area of the bed (m^2); Q_s, average flow (m s^{-1}); K_f, hydraulic conductivity of the media (m s^{-1}); dH/ds, slope (m m^{-1}).

Czech CWs are designed with an aspect ratio of less than two. The reason for a wider inflow rather than a long, narrow bed has been the assumption that this optimizes flow and diminishes clogging of the inlet. Evidence from Davison shows natural ways to minimize clogging by using earthworms (Davison et al., 2005). Clogging is also minimized by using larger gravel at the inlet, and, as previously mentioned, by proper maintenance of the primary treatment septic tank. Recent experiments in Spain indicate that aspect ratio is not as critical an element in bed flow mechanics as previously thought (J. Garcia et al., 2005). This conclusion for the warm weather of Spain may not necessarily apply to colder climates, because warm climate CWs sometimes have a high rate of water loss through evapotranspiration. This can change flow characteristics.

D) Depth and Bottom Slope

The 0.6-0.8 m depth of Czech beds was derived from the maximum depth of the macrophage root of the frequently used common reed (*Phragmites australis*). When coarse filtration materials are used, the Czech beds have a slope of less than 2.5%, and recently, with the more common use of finer pea gravel, slopes are often less than 1%. Garcia has proven that a water depth of 0.27 m yields the best removal efficiencies in a bed 0.6-0.8 m deep (J. Garcia et al., 2005). Garcia felt that the improved efficiency of shallower water depth was directly related to increased oxygen flux from the plants resulting in much higher rates of nitrification/denitrification (see section on nitrogen removal below). Wetzel had postulated that the downward pull of surface water by plant roots (that then pass it into the air through evapotranspiration) assured adequate mixing of water in deeper beds (Wetzel, 2001). Perhaps the apparent conflict is answered by research from Germany showing that almost all of the aerobic processes occur within 35 mm of the plant rhizosomes (roots) (Munch, Kuschk, & Roske, 2005).

An ideal residence time for these beds at 20^{o}C (68^{o}F) is approximately 5-7 days (Davison et al., 2005). Therefore, only a minimal bottom slope is necessary if substrate with excellent flow characteristics is used. Figure 4 shows a graph of residence time against percent BOD (Biological Oxygen Demand) remaining and percent nitrogen remaining. Davison clearly shows that little additional removal occurs after 7-8 days in warmer climates. This is less true for cold sewage and is the reason that insulation is important in colder climates (see section *"H" Insulation* below).

Figure 4: Percentages Remaining vs. Residence Time
(Davison et al., 2005)

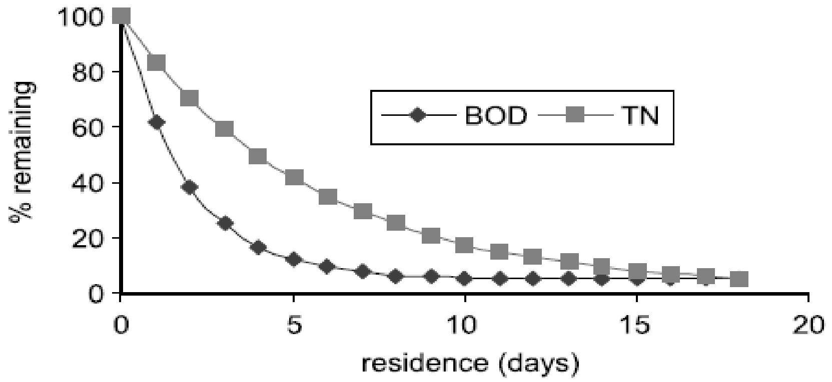


Figure 4 Percent of pollutant remaining versus HRT predicted by first order models at 20 °C

E) Filtration Media

Early Czech systems used soil materials that met the first two requirements for filtration media, that of facilitating macrophage growth and providing high filtration effect. They were deficient in maintaining high hydraulic conductivity (flow), the third requirement of an ideal media. The current use of 10 mm (#9) pea gravel has fulfilled all three requirements. Other authors have shown that coarser gravel at the inlet and outlet helps prevent clogging (Davison et al., 2005). Comparison research on attempting to identify the ideal adsorption media will be discussed under the treatment section. Garcia's work demonstrated a marked improvement in hydraulic loading rate (flow) for smaller gravel over larger substrate (J. Garcia et al., 2005).

F) Sealing the bed

Czech regulations, like those in most countries and the USA now require sealing with plastic liners between 0.8 and 2.0 mm thickness. These liners must be protected on both sides by geotextile or sand to prevent root penetration and damage by sharp edges. Clay liners were used in early Czech and North American CWs. An Australian manufacturer is producing an inexpensive plastic tub that is ready-made for home systems and makes construction simpler (Davison et al., 2005). The sealing of the bed allows CWs to be placed in areas with relatively high water tables where drain fields cannot function. As mentioned in *section B: Bed Configuration,* in the absence of a high water table, the second bed is best left unlined.

G) Vegetation

According to Vymazal, the most important effects of macrophages are erosion control, filtration, and provision of surface area for microorganisms (J. Vymazal, 2002). Very recent work has shown that oxygen flux from the plant is important for nitrogen removal, even though the SSFCW is primarily an anaerobic environment (Tanner & Kadlec, 2003). Munch and colleagues found that the ideal root rhizome separation was 35-70 mm, which coincidently is met exactly by *Phragmites australis* (Munch et al., 2005). Oxygen flux fell off rapidly after 35 mm from the root, so plants with rhizosomes wider apart than that will not be as efficient in nitrogen removal. A number of recent publications have proven significant differences amongst plant species in ability to degrade nitrogen (Allen, Hook, Biederman, & Stein, 2002; Picard, Fraser, & Steer, 2005; Stottmeister et al., 2003).

Vymazal measured significantly more bacteria on roots of *Phragmites* than on *Phalaris* (reed canary grass) (J. Vymazal, Balcarova, & Dousova, 2001a). Despite attempts to improve performance through mixing species, there is no solid evidence that such mixing does enhance results (Picard et al., 2005). In any event, after a few years, *Phragmites* tends to become dominant. Most planted wetlands receive some invasion from native species over time. Allen showed that all plants enhanced treatment capacity of SSFCWs compared to unplanted, and that plant effects and differences amongst species were much greater in air temperatures of 4^0C than at 24^0 C (Allen et al., 2002). Drizo documented that *Phragmites* enhanced nitrogen removal performance to a significant degree over unplanted cells (Drizo, Frost, Smith, & Grace, 1997). Nitrogen degradation has been one of the weaker aspects of on-site systems, including SSFCWs.

Maehlum and colleagues have suggested that aerobic pre-treatment makes plants unnecessary in horizontal subsurface-flow systems (T. Maehlum & Stalnacke, 1999). Although cost and maintenance make aeration problematic for smaller home systems, this step is an integral part of larger municipal plants where mechanical maintenance is practical. His study does prove that the primary function of the macrophage in nitrogen degradation is to provide oxygen for those processes. The authors demonstrated this by obtaining total **N** and ammonia **N** removal rates equal to CWs with plants by adding the aeration pre-treatment to cells without plants.

An interesting pilot study from Spain used wetlands for primary treatment of sewage from a small rural village (Solano, Soriano, & Ciria, 2004). These authors showed surprisingly good results for removal of Biological Oxygen demand (BOD), Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), and coliform bacteria even without pretreatment with a septic tank, but did conclude that pre-treatment would have greatly enhanced their results. Used as primary treatment, they found no difference between reed and cattail cells, at odds with studies quoted from other authors who used SSFCWs as secondary treatment.

H) Insulation

Vymazal uses nursery seedlings, which can be planted from May to October. He obtains sufficient coverage with a density of four to eight seedlings per m^2, and does not harvest them so that the litter can serve as insulation. He makes no other mention of insulation, but northern US experience has shown the benefits of using good insulation from the first planting (Picard et al., 2005; Wallace, Parkin, & Cross, 2001). This may include insulating the bed liner but more importantly, insulating the plants, after they are established, with quality mulch to cover the bed. These cold climate studies show that it is important to keep the septic influent warm as it flows through the wetland to maximize the functioning of microorganisms. Picard showed that the insulation effect is only important in the winter months. Wallace's 2001 study on types of insulation proved that wood chips, pine straw, and poplar bark were unsuitable, but that mulch consisting of reed-sedge peat or high quality yard waste compost produced effective insulation down to -20^0C. Kadlec performed a detailed analysis of thermal environments in Minnesota SSFCWs (Kadlec & Reddy, 2001). His analysis documented the necessity of using insulation to prevent freezing, whether that insulation was an early snow blanket or mulch. “Sites displayed no freezing when straw-mulched, despite extreme cold (average daily temperatures ranged down to -34^{0}C).” Minnesota’s climate is even more severe than Ohio’s and is a sterner test of the value of insulation.

2. Treatment Efficiency

The lack of standardized measurement methods for the five commonly reported effluent parameters presents one obstacle to comparison of treatment efficiency. The method of measurement was supposedly standardized and accepted worldwide in 1995 (American Public Health Association, 1995). It is still used by most authors publishing in the literature, but the literature review turned up a few articles where authors gave their measurement technique as conforming to EU methods or even French methods (Gasiunas et al., 2005; Merlin, Pajean, & Lissolo, 2002).

Research for the last 15 years has shown that CWs are more complex than conventional treatment processes due to the diffusive flow and the large number of processes involved in wastewater degradation. Removal efficiency is thus less easily predictable with the influence of these varying hydraulics and internal environment (Kadlec & Reddy, 2001). That complexity presents a barrier that needs to be overcome before SSFCWs can gain mainstream acceptance. It is well known that most of the bed is in an anaerobic environment. Munch showed that aerobic processes occurred primarily within 35 mm of the root (Munch et al., 2005). Conflicting results for years left unanswered the question of the relative importance of aerobic vs. anaerobic processes for removal of nitrogen products. This will be fully discussed in the section on nitrogen results (*d. Nitrogen*).

A more fundamental problem than measurement method in assessing the literature is the metric used to report results. This is variously given as percent removal, as effluent concentration, and as mass loading from the effluent. The EPA discharge standards are given as maximum concentrations allowed (Ohio Environmental Protection Agency, 2001b). It is obvious, however, that the most important impact on the environment is the total load released in the effluent. That is why some European countries set different discharge standards for different volume loads or population equivalents (H. Brix & Arias, 2005; Rousseau, Vanrolleghem, & De Pauw, 2004). The standards are less stringent for a single home discharging small volumes of effluent than for a municipal system discharging huge volumes. This issue will be further addressed in the section on policy recommendations.

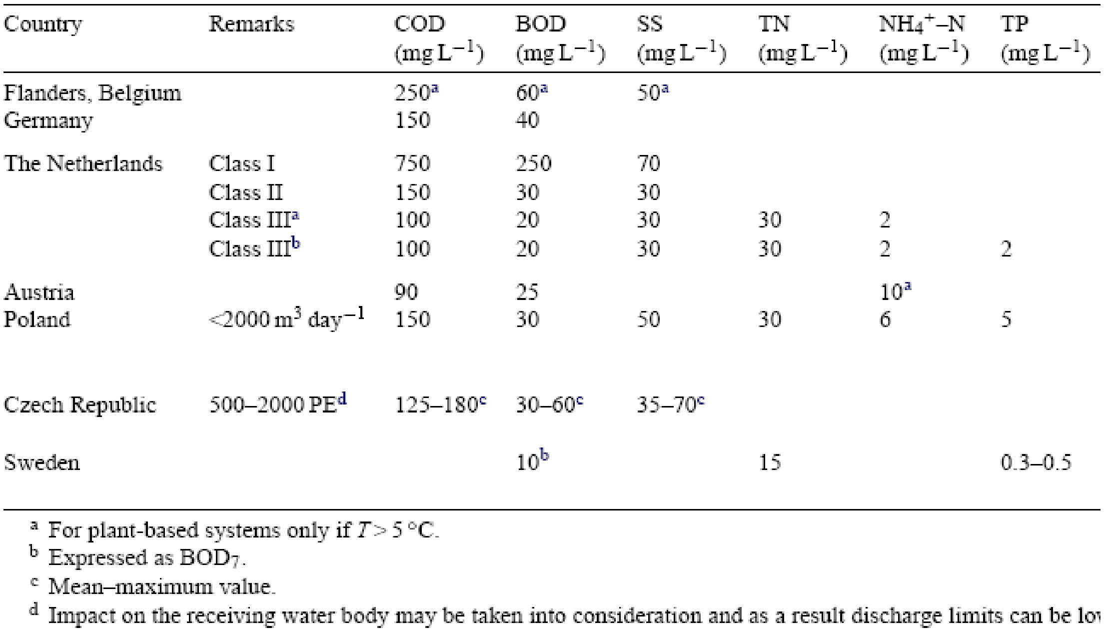
To quote Vymazal directly: “However, it could be misleading to evaluate the performance of CWs according to the treatment efficiency expressed as percentual removal. It has been well established that percentual efficiency increases with increasing inflow concentrations (e.g. Schierup et al., 1990a). In general, this principle applies to all kinds of wastewater technologies. In systems with low influent concentrations of pollutants (e.g. systems treating wastewater from combined sewerage or tertiary treatment systems) high quality effluent could be achieved with relatively low treatment efficiency calculated from inflow and outflow concentrations” (J. Vymazal, 2002).

Table 1: EPA surface discharge limits (maximum concentrations)
(Ohio Environmental Protection Agency, 2001b)

PATHOGEN	CONCENTRATION	UNITS
Fecal Coliform	**2000**	**counts/100 ml**
BOD_5	**15**	**mg/l**
TSS	**18**	**mg/l**
Ammonia	**1.5**	**mg/l**

Table 1 shows the strict OEPA discharge concentration limits (Ohio Environmental Protection Agency, 2001b). OEPA has also listed phosphorus limits at 1mg/l. Table 2, which follows, gives a comparison of European standards and it can be seen that they vary by country and within country by flow rates (Rousseau et al., 2004). Even these flow rates are not standardized and are based on population equivalents in the Czech Republic and on m3 day-1 in Poland. These standards actually refer to <2000m3/day as “small”. These two tables, taken together illustrate the issue of lack of standardization of effluent limits.

Table 2: European Effluent Standards
(Rousseau et al., 2004)



Country	Remarks	COD (mg L^{-1})	BOD (mg L^{-1})	SS (mg L^{-1})	TN (mg L^{-1})	NH_4^+–N (mg L^{-1})	TP (mg L^{-1})
Flanders, Belgium		250[a]	60[a]	50[a]			
Germany		150	40				
The Netherlands	Class I	750	250	70			
	Class II	150	30	30			
	Class III[a]	100	20	30	30	2	
	Class III[b]	100	20	30	30	2	2
Austria		90	25			10[a]	
Poland	<2000 m^3 day^{-1}	150	30	50	30	6	5
Czech Republic	500–2000 PE[d]	125–180[c]	30–60[c]	35–70[c]			
Sweden			10[b]		15		0.3–0.5

[a] For plant-based systems only if $T > 5$ °C.
[b] Expressed as BOD_7.
[c] Mean–maximum value.
[d] Impact on the receiving water body may be taken into consideration and as a result discharge limits can be lo

Perhaps Steer sums it up best: “There is a discrepancy between current US Environmental Protection Agency compliance standards and the USEPA National Pollution Discharge Elimination Systems Total Maximum Daily Load policy. Compliance concentration standards that were developed to conform to USEPA (2001) guidelines can be monitored quickly, at relatively low cost and rapidly evaluated as pass or fail. However, monitoring concentrations has limited usefulness for water resource managers because total loads delivered are of key importance to the overall health of the watershed" (D. Steer et al., 2002).

In light of these problems, Vymazal has presented some of the comparison data in both mass loading and percent removal values.. Additional data that gives discharge concentrations and mass loading is important in order to be able to compare studies and relate the results to published standards. His charts conveniently compare the Czech data with data from many other countries and North America.

Vymazal's data show that constructed wetlands with horizontal subsurface flow are very efficient in removing suspended solids (TSS). Much of this is due to the degradation processes in the pretreatment septic tank, so all on-site systems with such pretreatment are comparable in this aspect. In fact, as previously mentioned, the discharge of too much solid into any secondary treatment system will greatly shorten its life due to clogging. Organics, tested as BOD^5 (Biological Oxygen Demand) and COD (Chemical Oxygen Demand) are also degraded with high efficiency in the CWs reported by Vymazal. The removal efficiency of nitrogen and phosphorus is lower, and does not meet EPA standards as given above. Research presented under section "*D Nitrogen*" has shown efficient ways to solve this problem in SSFCWs. Fecal coliforms and other pathogens are removed with near 100% efficiency, but Vymazal does not report his results as colony counts per 100cc, which is the EPA measurement method. This makes comparison of the treatment performance difficult.

Vymazal does not mention start-up performance. Initial efficiency is important, as most single family wastewater treatment systems will not likely be built with a long interval before house occupancy. The system must be operative in a short time period. Several researchers have shown excellent start-up performance with continuing improvement over the first three years (J. Garcia et al., 2004; Vanier & Dahab, 2001). Finally, as previously mentioned, Vymazal admits that he does not have data for systems that don't discharge. It would have been very helpful to have included what percent of the Czech systems did not discharge. Part of the concern with SSFCWs is that they were originally designed to discharge, clearly against more recent EPA policy for home systems.

A) Organics (BOD)

As outlined in appendix 1 "*variables*", the removal of organics is an important reflection of water quality. The average removal of BOD^5 in the 38 Czech CWs was 88% (no EPA standard for %). The average outflow concentrations were 10.5 mg /l, within the OEPA limit of 15 mg/l. The average COD treatment efficiency was 75% with average outflow concentrations of 53 mg/l. Removal of COD was lower than BOD, due to the presence of non-biodegradable pollutants. No standards are set for BOD by the EPA or most countries. Removal did not have a seasonal pattern. Vymazal's country comparison data shows most systems removing organics to EPA standards.

B) Suspended solids (TSS)

The Czech data confirm high efficiency of TSS removal. Solid removal is important for water clarity and as a measure of purity. This averaged 84.3% and effluent concentrations averaged 10.2 mg/l. OEPA limits are 18 mg/l. Country comparisons show similar results that meet EPA standards.

C) Phosphorus

Release of phosphorus has significantly increased over the years through agricultural practices, industrialization, and urbanization. Nutrient enrichment, or eutrophication of aquatic ecosystems from nitrogen and especially phosphorus, can cause an increase in algae and aquatic plants, loss of natural component species, and eventually a loss of the natural ecosystem. Carpenter refers to eutrophication as the largest water quality problem in the world (Carpenter et al., 1998).

None of the results from the five countries or North America as given by Vymazal has shown phosphorus discharge concentrations less than 3 mg/l. The OEPA limits of 1 mg/l may be unobtainable by home systems unless special mechanical technology is used, or some of the substrates mentioned below prove economical in North America. Mechanical technology is best avoided. The goal as mentioned in “Introduction” is simplicity, low construction and maintenance cost, and minimal owner maintenance.

The primary mechanisms for removal of phosphorus mentioned by all authors are chemical precipitation and physico-chemical sorption. Macrophages thus play little role in phosphorus removal. The stone filtration media commonly used are chosen to maintain a high hydraulic conductivity and do not have the adsorptive capacity of earth media that the earliest systems used. Vymazal indicates that his earth systems clogged very early and were not suitable for SSFCWs (J. Vymazal, 2002). Some recently replicated experiments that searched for substrates with high conductivity and high phosphorus adsorption have shown shale and ceramic media to have high efficiencies that have been maintained for as long as 15 years (H. Brix, Arias, & del Bubba, 2001; Drizo et al., 1997; Drizo, Frost, Grace, & Smith, 1999; Forbes et al., 2005). The experiments by Drizo on phosphorus removal properties of seven different substrates proved that shale had the "best combination of properties as a substrate for CWs", in both the short-term and the long-term (Drizo et al., 1999). Drizo's earlier work had indicated that CWs with shale substrate and *Phragmites* macrophages had phosphorus removal efficiencies of an unheard of 98-100% (Drizo et al., 1997). Equally important was the data showing ammonium **N** removal of virtually 100% and nitrate **N** removal between 85 and 90%. This indicates that with appropriate substrate, plants with their attached microbes do in fact actively participate in **P** and **N** removal.

A 2002 article from Germany determined that the addition of iron filings to the filter material (pea gravel) was more effective in ensuring a sustainable high removal capacity of phosphorus than calcium rich soil (Luderitz & Gerlach, 2002). The authors showed that *Phragmites* increased the phosphorus removal rates to 97% from 50%. These figures are dramatic and replicate that of Drizo. There is little doubt that in suitable conditions, plants are important "in microbiological **P** transformation processes and in the direct elimination of **P** by binding" (Luderitz & Gerlach, 2002). It appears that the presence of iron is the key to involving the plant in phosphorus removal. This research provides some long-needed answers to improving nitrogen and phosphorus discharge. Note the continuing theme of common reed (*Phragmites australis*) being mentioned as an efficient plant in most of the wetland studies.

D) Nitrogen

The majority of nitrogen in home systems is ammoniacal nitrogen. Other nitrogen species in wastewater are ammonia, organic-N, and nitrate-N (Tanner, Kadlec, Gibbs, Sukias, & Nguyen, 2002). In addition to the total load of nitrogen discharged to the environment, the form of N may be a crucial factor impacting the effect on that environment. In particular, ammoniacal-N can be toxic to aquatic biota (Tanner et al., 2002). Ammoniacal nitrogen removal rates in the Czech reports averaged 43%, but the individual rates ranged from 9-73%. Based on oxygen flux rates, some of these results are much higher (better) than would be projected (Tanner & Kadlec, 2003). Vymazal's effluent concentrations averaged 16.1 mg/l. This is unacceptable and above the OEPA maximum of 1.5 mg/l. The pooled studies from other countries showed efficiency rates varying from 21-56%. They also had very little seasonal variation.

The early work on CWs showed such systems to be no better than other on-site systems at nitrogen removal. It was proven that planted wetlands were more efficient at nitrogen removal than unplanted ones, but results were still well below requirements (Allen et al., 2002). It was assumed that oxygen flux from the plant roots into the anaerobic milieu was the primary reason for the benefit from plants. To this day, researchers have been unable to explain the incredible day-to-day and diurnal variation in nitrogen removal in individual CWs, a variability that far surpasses any seasonal differences (Axler et al., 2001; Kuschk et al., 2003).

Current research on CWs focuses on understanding and improving nitrogen degradation. Earlier work had shown that volatization, ammonification, plant uptake, nitrification/denitrification, and matrix absorption all play a role in total nitrogen removal. However, until recently it was agreed that nitrification/denitrification was the most important process for nitrogen removal. This meant that the limiting step was the nitrification process, which requires oxygen. Plants have a finite ability to flux oxygen to the roots, an ability that is further reduced in cold weather (Kuschk et al., 2003). There is evidence that dissolved organic carbon, as shown by a high BOD, is required to drive the denitrification process and some of this is provided by the plants (Bayley, Davison, & Headley, 2003).

The recent experiments of Tanner have suggested that alternate pathways with an anaerobic engine may be the reason that removal rates are higher than theoretically possible based on the oxygen available from the plant (Tanner & Kadlec, 2003). Tanner mentions that other researchers had proven the existence of anaerobic ammoniacal oxidative pathways in nature, and had also shown several ways that “aerobic” oxidizers could denitrify in anaerobic conditions. The studies by Luderitz on the use of iron filings may be the answer to the **N** removal problem, as well as the phosphorus removal problem (Luderitz & Gerlach, 2002). As mentioned, he and independent researchers have obtained ammoniacal N removal rates of essentially 100% with the presence of iron in the substrate. This research has been replicated enough to recommend it as the solution to the unacceptable rates of nitrogen degradation. The nitrogen removal variability amongst seemingly similar systems has been a barrier to full acceptance of this technology.

Based on a recent article about gaseous emissions from CWs, it would appear that their use for **N** removal does not contribute significantly to greenhouse effect (Mander et al., 2003).

E) Microbial pollution

SSFCWs show removal efficiencies of close to 100% for coliform and other bacteria (Barrett, Sobsey, House, & White, 2001). The mechanisms according to Vymazal include physical factors (filtration, sedimentation, aggregation, and ultra-violet action), chemical systems (oxidation, adsorption, and toxins), and biological mechanisms (antibiotics, ingestion by nematodes and protozoans, lytic bacteria, and bacteriophages). Vymazal showed a steep decrease in bacterial numbers within the first few meters of the bed (J.

Vymazal et al., 2001a). Seeding experiments by Axler using *salmonella*, proved removal efficiencies of 95% in winter and 99.8% in summer (Axler et al., 2001). This would normally meet EPA standards when converted to colony counts per 100 ml.

Vymazal does not provide data to compare to the EPA standard of <2000 counts/100 ml. Axler showed consistent disinfection to <200 fecals/100 ml year-round. Stott performed laboratory feeding experiments that showed protozoan predation (as occurs naturally in CWs) to be an efficient mechanism for removal of *Cryptosporidium* oocysts (Stott, R., May, E., Matsushita, E., & Warren, A, 2001). This is important because *Cryptosporidium* outbreaks are becoming increasingly recognized worldwide, and because ordinary chlorination does not destroy the cysts. These studies have been confirmed by Quinonez-Diaz who documented a better than 90% removal of bacteria, *giardia*, *cryptosporidium*, and enteric viruses with only a two day retention time, much less time than is the norm for most CWs (Quinonez-Diaz, Karpiscak, Ellman, & Gerba, 2001). The experiment also demonstrated superiority for planted as opposed to unplanted CWs in this pathogen removal.

3. Costs

The capital costs in the Czech Republic are about the same as an equivalent conventional system without special nutrient removal mechanisms, with 70% of this cost coming from the filtration material and excavation (J. Vymazal, 2002). Both Davison and Axler conclude that compared to other technologies, CWs are relatively inexpensive to build and maintain (Axler et al., 2001; Davison et al., 2005). Davison states that “the reed bed (CW) is relatively cheap to build, requires no power to operate and very little personal effort or money to maintain. From the treatment perspective, the reed bed has been found to exhibit a superior nitrogen removal capacity to aerated wastewater treatment systems and single pass sand filters”.

Recent cost estimates from the City of Austin website are included below and compare quite favorably to other on-site technology. “O&M” is the costs for operation and maintenance (City of Austin-Onsite Treatment (Pretreatment) System Fact Sheets, Retrieved February 3, 2006). It is not clear where these costs come from, as the Logan County wetlands have no maintenance costs except for pumping the septic tank every five or so years.

Figure 5: Cost Studies from the City of Austin Fact Sheet

Wetland unit, installed, and including septic tank for pretreatment,	$8,000
Septage and sludge pumping estimated at once every 3-1/2 years,	$4.17/month
O&M, with a maintenance contract of $180/year (est. 6 hrs. @ $15/hour * 2.0, including taxes, overhead, and profit),	$15/month
20-year NPW (not incl. design & permitting costs),	$10,291.86

A cost study was completed in April 2006 in Logan County. This showed a favorable cost comparison to tile beds. With the addition of pure iron filings making up 1% of the substrate (Luderitz & Gerlach, 2002) to obtain >95% phosphorus and nitrogen removal, the cost per wetland cell was quoted at $2500 planted. The standard $1500 septic tank cost gives a total outlay of $6500. If a small leach field is added for tertiary treatment in place of the second cell, the total cost reaches $8000 ($4000 for tile field). Mounds are currently being priced in Logan and surrounding counties at $15-20,000. Several of the Logan County CWs are routed into small leaching fields after one cell where treatment is completed without discharge. Maintenance cost, aside from pumping of the septic tank has been minimal.

META ANALYSIS

A literature review can have numerous different focuses and goals. Integrative research reviews summarize past research by drawing overall conclusions from many studies that address particular issues about the chosen topic. Meta-analysis is a synthesis of available literature about a topic, and statistical analysis of the pooled data chosen to arrive at a summary estimate of the effect, a confidence interval, and a test of homogeneity of the studies. If the data is reported in several ways that cannot be standardized, then a descriptive analysis is an alternative means of describing the results (Rosenthal, 1991).

The purpose of this paper was to review the current state of SSFCW technology, and through rigorous scientific evaluation, decide whether SSFCWs could meet EPA standards and be recommended for adoption in Ohio. The author conducted such a search of the Web of Science database on March 24, 2006.

Search Methods and Rationale

1) Step #1

A topic search (TS) for *constructed wetland* or *horizontal subsurface flow wetland* or *treatment wetland* from 1986 to March 24, 2006 was conducted in Web of Science. 1986 was used even though the database allowed a search back to 1980. The author had not found any studies published before 1986 that had not used earth media as substrate. These all clogged early and so earth had been deemed at that time to be an inappropriate substrate (Vymazal 2002). In fact, the step # 4 search did not yield any articles prior to 1992. The study was not limited to those published in English. "Topic" was used in the first two steps to allow as broad a search as possible. This yielded 1400 references.

2) Step #2

In order to pare this number down to a manageable number of abstracts to review, a topic search (TS) was done to eliminate constructed wetlands that were not subsurface flow design. As discussed in "*Introduction*", constructed wetlands can be of many types. Thus, the search used the names: "subsurface flow, subsurface-flow, sub-surface flow and reed bed". "Domestic effluent" was used to capture titles that did not mention subsurface flow, but were studies on CWs treating domestic effluent. This search yielded 340 references.

It should be mentioned that during reading on this topic over the previous year, the author had identified 12 articles that he considered to be key studies of SSFCW performance. At each step, the yielded references were checked to insure that these articles were included. The author felt that their inclusion would be a good guide to the legitimacy of the search.

3) Step #3

A title search was used as indicated (NOT TI, not title) to eliminate studies that were deemed not appropriate for studying domestic wastewater treatment in horizontal SSFCWs in a climate such as that of Ohio. This elimination was not done for "abstract" search because an abstract has so many words that such a search for "not" would have eliminated most studies. It was planned to do that elimination by reading each of the remaining abstracts (step # 5).

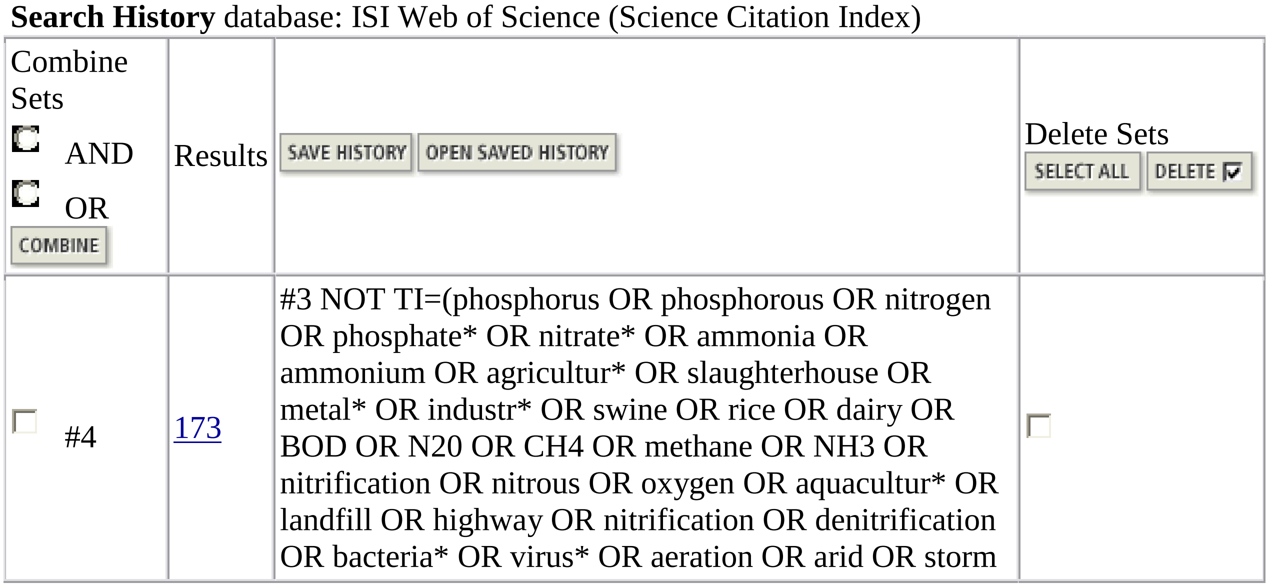
The author made the decision to eliminate studies from hot weather climates, because it was known that SSFCWs in such climates were more efficient than wetlands from cold climate that were not insulated. At the time of completion of this paper, the author believed that there was proof that insulation allowed SSFCWs to function as efficiently in cold weather as in warm weather. He now feels that some excellent studies were eliminated

(Davison). This search was conducted to eliminate (NOT TS) the hot climates of: tropic, desert, Africa, Costa Rica, Caribbean, Mexico, India, and Nepal. Also listed for elimination were treatment of wastewater not from domestic source (mine, farm). The purpose of this paper was to study home wastewater treatment. This search left a further 271 studies.

4. Step # 4

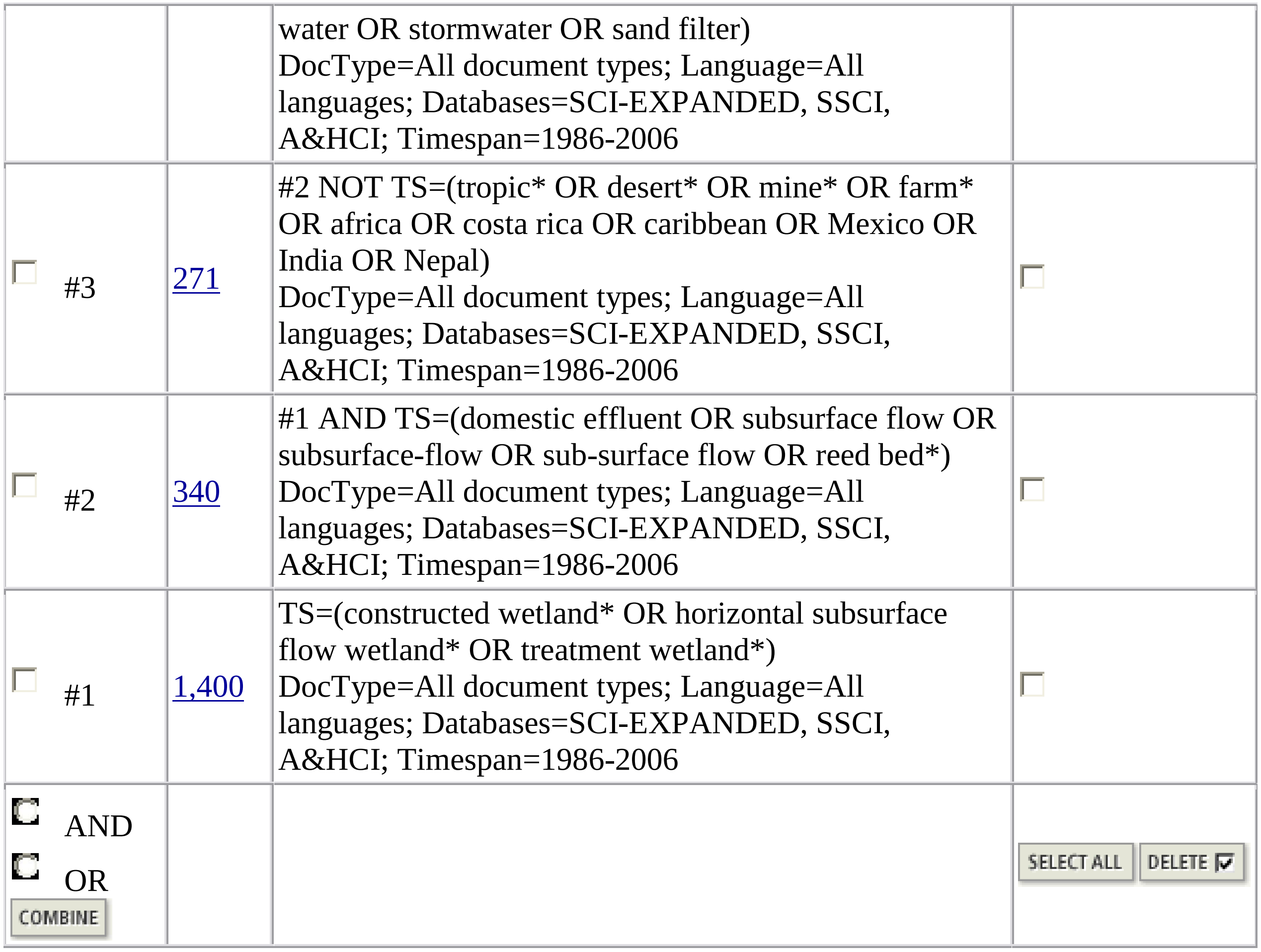
This was the first "title" search ("NOT TI"). The author's goal in the step was to eliminate all studies on treatment of wastewater from sources that were not domestic. This was done by using words that he knew named other types of wastewater (such as aquaculture, industrial, dairy, swine, and rice). Also included for elimination were titles containing the names aeration and sand filter, because the Meta-analysis was to be on SSFCWs, without such pre-treatment. Finally, it was felt that articles that specified single parameters in the title (such as nitrogen, phosphorus, BOD, and nitrification) were focused studies on degradation of those specific toxins and would not give results for the other 4 parameters. By the end of step #4 there was 173 articles identified.

Table 3: Method of Search from Web of Science (March 24, 2006)



Search History database: ISI Web of Science (Science Citation Index)

Combine Sets ○ AND ○ OR COMBINE	Results	SAVE HISTORY OPEN SAVED HISTORY	Delete Sets SELECT ALL DELETE
☐ #4	173	#3 NOT TI=(phosphorus OR phosphorous OR nitrogen OR phosphate* OR nitrate* OR ammonia OR ammonium OR agricultur* OR slaughterhouse OR metal* OR industr* OR swine OR rice OR dairy OR BOD OR N20 OR CH4 OR methane OR NH3 OR nitrification OR nitrous OR oxygen OR aquacultur* OR landfill OR highway OR nitrification OR denitrification OR bacteria* OR virus* OR aeration OR arid OR storm	☐



		water OR stormwater OR sand filter) DocType=All document types; Language=All languages; Databases=SCI-EXPANDED, SSCI, A&HCI; Timespan=1986-2006	
☐ #3	271	#2 NOT TS=(tropic* OR desert* OR mine* OR farm* OR africa OR costa rica OR caribbean OR Mexico OR India OR Nepal) DocType=All document types; Language=All languages; Databases=SCI-EXPANDED, SSCI, A&HCI; Timespan=1986-2006	☐
☐ #2	340	#1 AND TS=(domestic effluent OR subsurface flow OR subsurface-flow OR sub-surface flow OR reed bed*) DocType=All document types; Language=All languages; Databases=SCI-EXPANDED, SSCI, A&HCI; Timespan=1986-2006	☐
☐ #1	1,400	TS=(constructed wetland* OR horizontal subsurface flow wetland* OR treatment wetland*) DocType=All document types; Language=All languages; Databases=SCI-EXPANDED, SSCI, A&HCI; Timespan=1986-2006	☐
○ AND ○ OR COMBINE			SELECT ALL DELETE ☑

5) Step #5

The abstracts from each of the remaining 173 articles were reviewed on-line. The article was eliminated and the full PDF file not downloaded if it was deemed to be unsuitable for the reasons that are now discussed. The topic of this paper is specifically on the use of horizontal SSFCWs for secondary treatment of domestic wastewater without mechanical pre-treatment. Abstracts were removed from further study if they indicated the SSFCW was for primary or tertiary treatment, if there was any mechanical or aerobic pre-treatment, if the wetland was free water surface, or if vertical CWs were used in combination. There were a number further eliminated because they were laboratory models, not actual working SSFCWs, because they were not treating domestic wastewater, or because they were studies on single parameters, as was discussed in steps 2-4 above. This left a final 43 articles for full study that were downloaded from Ohio Links or requested via interlibrary loan.

6) Step # 6

The 43 articles were studied closely to ascertain their appropriateness for inclusion in a Meta-analysis. The criteria were that the articles must be studies on treatment results from horizontal subsurface flow constructed wetlands used for secondary treatment of domestic wastewater in a climate similar to or colder than that of Ohio. The reasons for exclusion were often because the full text uncovered one of the criteria for elimination that had already been a part of steps 1-5. The reasons for exclusion are documented for each of the articles in the table below. Six were from tropical or sub-tropical climates. Seven gave no data on use as secondary treatment. Eight were eliminated because they had aerobic pre-treatment.

Table 4: 43 Articles For Inclusion Or Exclusion With Rationale				
ITEM #	**AUTHORS**	**EXCLUDE / INCLUDE**	**RATIONALE**	**ISSUES**
1.	(Al-Omari & Fayyad, 2003)	Exclude	Subtropical Desert - Jordan	
2.	(Axler et al., 2001)	Include	Cold - Minnesota	Not insulated
3.	(Begg, Lavigne, & Veneman, 2001)	Exclude	Aeration Pre-Treatment	
4.	(Bhamidimarri, Shilton, Armstrong, Jacobson, & Scarlett, 1991)	Exclude	Aerobic Pre-Treatment	
5.	(H. Brix, 1994)	Include	Summary of 101 Systems	No documentation of types of pre-treatment; world-wide
6.	(Brown & Reed, 1994)	Exclude	Aerobic Pre-Treatment or unclear	
7.	(Conte, Martinuzzi, Giovannelli, Pucci, & Masi, 2001)	Exclude	Warm Climate - Italy	
8.	(Cooper, 2001)	Include	Cold - England	Only used results after 1990 due to run off from farms earlier
9.	(Cooper, Willoughby, & Cooper, 2004)	Exclude	Sludge degrading	
10.	(Dahab & Surampalli, 2001)	Include	Cold - Nebraska	
11.	(Dahab, Surampalli, & Liu, 2001)	Exclude	Modeling #10	
12.	(Davison et al., 2005)	Exclude	Sub-Tropics - Australia	Great study, one of recent best
13.	(Gasiunas et al., 2005)	Include	Cold-Lithuania	
14.	(Geller, 1997)	Include	Cold - Germany	
15.	(Giaever, 2000)	Exclude	Aerobic Pre-Treatment	
16.	(Griffin, 2003)	Exclude	Tertiary Treatment	
17.	(Griffin & Pamplin, 1998)	Exclude	Insufficient data on secondary	
18.	(Griffin & Upton, 1999)	Include	England, secondary Rx	
19.	(Gschlossl & Stuible, 2000)	Exclude	Only BOD, COD parameters	
20.	(Ham, Yoon, Hwang, & Jung, 2004)	Include	Cold-China	
21.	(Hench, Sexstone, & Bissonnette, 2004)	Include	Cold-West Virginia	

Table 4: 43 Articles For Inclusion Or Exclusion With Rationale

ITEM #	AUTHORS	EXCLUDE / INCLUDE	RATIONALE	ISSUES
22.	(Jenssen, Maehlum, & Krogstad, 1993)	Exclude	Aerobic Pre-Treatment	
23.	(Lakatos, Kiss, Kiss, & Juhasz, 1997)	Exclude	No secondary treatment results	
24.	(Langergraber & Haberl, 2001)	Exclude	No data on 5 parameters	
25.	(Li & Chuncai, 1995)	Exclude	Open Wetlands	
26.	(Luederitz, Eckert, Lange-Weber, Lange, & Gersberg, 2001)	Include	Cold-Germany -	Pre-treat chamber has wood shavings
27.	(T. Maehlum, Jenssen, & Warner, 1995)	Exclude	Aerobic Pre-Treatment	
28.	(T. Maehlum & Stalnacke, 1999)	Exclude	Vertical Flow Pre-Treatment	Amazing results combined CW in cold climate
29.	(Merlin et al., 2002)	Include	Cold-France Mountains	
30.	(Perfler & Haberl, 1993)	Include	Cold-Austria	
31.	(Philippi, da Costa, & Sezerino, 1999)	Exclude	Brazil - Subtropical, no temperatures given	
32.	(Reed & Brown, 1995)	Exclude	Large flows, no pre-treatment data	
33.	(Richter & Weaver, 2003)	Exclude	Warm-Texas	
34.	(Rousseau et al. 2004)	Include	Cold-Belgium	
35.	(Srinivasan, Weaver, Lesikar, & Persyn, 2000)	Exclude	Subtropical	
37.	(D. Steer et al., 2002)	Include	Cold-Ohio	
36.	(D. Steer, Fraser, & Seibert, 2005)	Include	Further studies on 8 from #37	
38.	(Vanier & Dahab, 2001)	Exclude	Same as #10	
39.	(J. Vymazal, 2002)	Include	Cold-Czech Republic	
40.	(J. Vymazal, 2005)	Include	Detailed update of 2 systems from # 39	
41.	(Wallace et al., 2001)	Exclude	Study on types of mulch	
42.	(Wittgren & Maehlum, 1997)	Exclude	No Data	
43.	(Yoon, Kwun, & Ham, 2001)	Exclude	More complete data in Ham # 20	

A final group of 16 articles was selected based on the inclusion and exclusion criteria. These articles were published from 1993 to 2005. They included studies from 13 countries and a number of US states.

Special comment on Vymazal’s 2002 review article is necessary (J. Vymazal, 2002). His North American results were from a source published after Brix’ 1994 review and were from a smaller number of systems than Brix had listed (H. Brix, 1994). They were thus included. The comparison results given for Denmark were not included in the spreadsheet because these came from Brix and the author knew from prior research that virtually all of Brix recent designs in Norway and Denmark included a vertical flow pre-treatment step.

Table 5: Included Articles

Author	**Year Published**	**Location**	**Climate**	**Size**	**Res Time**	**Flow**	**Medium**	**Plant**	**Method Analysis**	**TSS mg/l**	**BOD 5 mg/l**	**Nitrogen mg/ml**	**Total P mg/l**	**Fecal Coliform**
(Axler et al., 2001)	2001	Minnesota, USA (3 yrs)	Cold November - April 2.6°C to < -40°C	1) 2=75 m^2 2) 2=480m^3	1=13 d 2=23d	1)95 m^3/d 2) 4 m^3/d	Gravel	Typha & Scirpus	APHA 1995 1) mass removal 2)concentration	1) S= 8±2 85% W= 9(85%) 2) S =5(82%) W= 6(73%)	1) S=23±10 (92%) w=51+/-17 79% 2) S=45(76%) W= 86(49%)	1) Average 42% 2) S=48(20%) W =45(21%)	1) S=51% W =20% 2)S=5.9 (30%) W =6.6 (15%)	1)S=99%ann mean 491/100 2) S =99.7% 443/100ml W=98.9% 1265/100ml
(H. Brix, 1994)	1994	World	Warm & Cold (most)	104 systems		.05-.5m/d	Gravel		*gives only frequency distributions for parameters	24 mean	17 mean	10.2 mean	5.9 mean	
(Cooper, 2001)	2001	England (1 yr)	Data on series beds only	5.6m^2/PE		30PE	Average 1yr			22mg/l 93%	15mg/l	amm N=39.7 Kjeldahl N=0 Oxidized N=3.4		
(Dahab & Surampalli, 2001)	2001 (3.5 yrs)	Nebraska, USA	Cold	4x125=500		120m^3/d	Gravel	Typha, Scirpus, Phragmites	APHA 1995 or EPA	S 3.3 (1.4-8.6) W 2.4 (1.4-3.8) 95.70%	S=18.7 (2.3-48) 83% W=19.3 (8.1-31.2) 79%	S=NH4N=13.7(2.1-23.2).NO3N=2.2(0.6-4)43% W=NH4N=15.3(8.617.8)14%NO32.5(1.7-4.5)30.4%	S=2.3 (0.6-4.5) 21% W=2.2 (0.9-3) 12.6%	S=18.800 (<200->110,000) 1.9 log redn W=13,600 (1700->50K) 1.78 Log rdn

Table 5: Included Articles

Author	Year Published	Location	Climate	Size	Res Time	Flow	Medium	Plant	Method Analysis	TSS mg/l	BOD 5 mg/l	Nitrogen mg/ml	Total P mg/l	Fecal Coliform
(Gasiunas et al., 2005)	2005 (8 yrs)	Lithuania	Cold (winter ave -5.10C)	360m²		40-60			EU Standards		8.6±4.3 81%	Total N 13.5±5.7 47.9%	1.12±0.84 61.4%	
(Geller, 1997)	1997	Germany	Cold	2x600m2 2x1000m2 4x1300m2	>14d	10-60m²	Sand	Phragmites, Iris			Average all 2mg 100%	Total N 27 98%	Total P 0.8 98%	
(Griffin & Upton, 1999)	1999	United Kingdom (>5yrs)		5m²/PE		<50PE	Gravel	Phragmites		15mg/l	22mg/l	AmN 39.7 Total N 3.4		
(Ham et al., 2004)	2004	Korea (4 yrs)	Average Winter -0.2°C	16m² one bed	3.5d	6.3cm/d	Sand	Phragmites	standard methods	S 14.0±11.4 71.6%±23.34% W 32.8±19.14 64.8%±20.19	S 20.9±17.98 81%±12.78 W 62.2±48.63 61.8%±15.13	TN:S 93.9±35.47 20%±28.00 W 108.0±36.18 7.7%±12.91	S 7.1±3.58 44%±33.2 W 8.5±2.81 26.8±27.15%	
(Hench et al., 2004)	2004	West Virginia, USA (2 yrs)				19L/day ?	Pea Gravel	Typhus, Scirpus	APHA 1995	S 3.4 (1.05 SE) W 68.5 (35.4)	S 84.3 (26.8 SE) W 107.6 (32.2)	TKN S 5.9 (2.1) W 5.6 (1.3)		S 5.7 (0.3) W 6.1 (0.4)
(Merlin et al., 2002)	2002	France	Average Winter 8.6°C	(3 beds)	4-5d	350PE	Pea Gravel	Phragmites, Typhus, Scirpus	French or APHA	95.6% +/- 3.6%	89.4 +/- 9%	57.3%± 21.2%	69.4% ± 27.1%	99%
(Perfler & Haberl, 1993)	1993	Austria (1 yr)		52.5m²		10PE	Gravel	Phragmites	DEV Standard		37-78%	NH4N 39-48% Total N 47-49%	2mg 80%	

Table 5: Included Articles

Author	Year Published	Location	Climate	Size	Res Time	Flow	Medium	Plant	Method Analysis	TSS mg/l	BOD 5 mg/l	Nitrogen mg/ml	Total P mg/l	Fecal Coliform
(Rousseau et al., 2004)	2004	Flanders, Belgium		1) 896m^2 2) 1300m^2		1)152PE 2)350PE	Gravel	PA	*All given as cumulative frequency distribution curves	86%	COD 72%	TN 33%	48%	
(D. Steer et al., 2002)	2002	Ohio, USA 21 systems (7 yrs)				2-7 PE	Gravel	Scirpus, Saggitarius, ornamental	EPA '83	55.8%±52.8 79% of the time meets EPA standards	70.3%±48.5 89% of the time met standards	NH3N:56.5±31.36 10% samples met standards	80.5±19.8% 50% of the time met standards	87.9±27.16 74% of the time met standards
(D. Steer et al., 2005)	2005	Ohio, USA 8 systems (2 yrs)	Cold	2 cells each 25m^2 Subdivided by large & small systems		2-7PE	Gravel	Sirpus, Saggitarius, ornamental	as 2002, but confusing data as removed outliers	83% & 77% 2 groups with sig p value all	91% & 86% 2 groups 13.8±3.2	amm N 70% 9.14+/- 1.23 met standards<50% time	55% 2.79±0.4 met standards 55% time	99% 1248/100 ±326
(J. Vymazal, 2002)	2002	Czech Republic and compare to several countries and continents	Cold				Gravel	Phragmites, Typha, Iris		42systems. a)conc: 84.3% 36systems. b)mass:88.5%	55 systems a)concentration eff: 88% 29systems b)mass loading eff: 83.5%	TN:33systems. a)conc: 41.6% 29 systems b) mass:38.9% ammmon.N37 syst a) conc:42.7% b)mass:37.4%	32systems a)conc:51% 30systems b) mass:42.5%	

Table 5: Included Articles

Author	Year Published	Location	Climate	Size	Res Time	Flow	Medium	Plant	Method Analysis	TSS mg/l	BOD 5 mg/l	Nitrogen mg/ml	Total P mg/l	Fecal Coliform
(J. Vymazal, 2002)	2002	Compared to North America	Cold							34systems. a)conc:78.6% 29systems b)mass:73.4%	34 systems a)conc.:68.5% b)mass:63.0%	12systems. TN a)conc:55.6% b)mass:44.3% ammN19syst a)conc:24.6% b)mass15syst: 8.6% ammonN conc:Saxony 45syst:54.0%	8systems a)conc:32.7% b)mass:22.2%	
		a)Germany-Saxony b)Germany-Bavaria									39 systems a)conc.:83.0% 7systems. b)conc.:79.6%	a)9systems conc:48.0%	26systems a)conc:65%	
		Poland								6systems. a)conc:77.4% b)mass:62.2%	6systems .a)conc:83.5% 6systems b)mass:81.2%	6systems a)conc:24.5% b)mass:20.9%	5systems a)conc:46.4% b)mass:41.2%	

Table 5: Included Articles

Author	Year Published	Location	Climate	Size	Res Time	Flow	Medium	Plant	Method Analysis	TSS mg/l	BOD 5 mg/l	Nitrogen mg/ml	Total P mg/l	Fecal Coliform
		Slovenia									3systems a)conc:89.0 b)mass:89.8%	3systems a)conc:73.2% b)mass:74.1%		
		Sweden									3systems a)conc:92.7% 2systems b)mass:86.2%	3systems. a)conc:40.3% 2systems. b)mass:44.9%	3syst.a)conc:58.3% 2syst. b)mass:61.4%	
(J. Vymazal, 2005)	2005 (1 1/2 yrs)	Czech Republic (selected 2 systems from 2002 for further study)	Cold	System 1)18m^2		1) 4 PE	Coarse Sand	Phragmites, Typha, Iris		1)9.1 99%	1)9.7 97%	NH 51 14% NO3 2.9 Norg 1.1 95% TN 55 35%	10.6 38%	
				System 2) 2500m^2/4 beds		2) 700PE 200m^3/d				2)9.5±8.0 90%	2) 4.6 80%±3.4	NH4 9.4±5 19% NO3 1.79±2.2 40%	2.09±1.52 7%	5.01±5.42 1.1 log

RESULTS

1) TSS

Table 6: TSS Results

Author	Number CWs	Area or Flow	Removal mg/l (EPA max.18)	Removal Percentage
1. Axler	2	75&480m²	1) S:5; W:6 2) S:8(=/-2) W:<9	85 85
2. Brix	104		Mean:24	
3. Cooper		5.6m²/PE	Mean:22	93
4. Dahab	1	500m²	S:3.3(1.4-8.6) W:2.4(1.4-3.8)	96
5. Gasiunas		360m²	8.6±4.3	81
6. Geller	8	600-1300m²	Mean:2	100
7. Griffin		5m²/PE	15	
8. Ham	1	16m²	S:14±11.4 W:32.8±19.14	71.6±23.34 64.8±20.19
9. Hench			S:3.4(SE:1.05) W:68.5(SE:34.4)	
10. Merlin		350PE		95.6±3.6
11. Perfler		52.5m²		
12. Rousseau	2	896 &1300m²		Met Flemish standard 100% time
13. Steer (2002)	21	2-7PE	18.8 SD17.3	55.8±52.8 Met EPA standards 79% of the time
14. Steer (2005)	8	2-7PE	Average<18	80 Met EPA standards>95% of the time
15. Vymazal (2002)				
a) Czech Republic	42	18-4500m2	10.2 SD:6.9	84.3 by concentration
	36			88.5 by mass load
b) North America?	34		10.3	78.6 conc.
	29			73.4 mass
c) Germany				
d) Poland	6		38.6 SD:23.5	77.4 conc.
				62.2 mass
e) Slovenia				
f) Sweden				
16. Vymazal (2005)	2	1)18m² 2)2500m²	9.1 9.5±8.0	99 90
Legend:				
mg/l: milligrams per liter	S:summer W: winter			
m2:square meters	PE:population equivalent			

As will be outlined in the “discussion” section, the lack of standardization in reporting metrics used by different authors makes analysis and conclusions difficult. If one considers only those studies where the results are given as mg/l (the method used for EPA standards), there are eleven of the reported groups that meet the EPA standard of 18mg/ml, and five that do not. This is not sufficient power to recommend constructed wetlands for approval to EPA standards. It is not instructive to perform further detailed analysis because of the tremendous variability and lack of comparability of the different volumes treated in the studies. In fact, only five of the studies reported give sufficient information to conclude that the results are from systems with a size comparable to a home system (<7 population equivalents or < 50 m^2). In any event, as with all on-site systems, it is the proper design and maintenance of the pre-treatment septic tank that is the most critical component of solids removal from domestic wastewater.

2) BOD

Table 7: BOD$_5$ Results

Author	Number CWs	Area or Flow	Removal mg/l (EPA 15)	Removal Percentage
1. Axler	2	75&480m²	1) S:30 2) 45	92 79 82 73
2. Brix	104		Mean:17	
3. Cooper		5.6m²/PE	15	
4. Dahab	1	500m²	S:(8.7)(2.3-48) W:19.3(8.1-31.2)	83 79
5. Gasiunas		360m²	8.6±4.3	81
6. Geller	8	600-1300m²	2mg	100
7. Griffin		5m²/PE	22	
8. Ham	1	16m²	S:20.9±17.98 W:32.8±19.14	81±12.78 64.8±20.19
9. Hench			S:84.3(SE:26.8) W:107.6(32.2)	
10. Merlin		350PE		89.4±9
11. Perfler		52.5m²		37-78
12. Rousseau	2	896 & 1300m²		Meets Flemish standards 100% of the time
13. Steer (2002)	21	2-7PE	13.7 SD: 18.4	70.3 SD:48.5 Met EPA Stds 89% of the time
14. Steer (2005)	8	2-7PE	13.8±3.2	
15. Vymazal (2002)	55			88 conc.
	29			83.5 mass
a) North America	34			68.5 conc.
				63 mass
b) Germany	39			83
	7			79.60
c) Poland	6			83.5 conc.
				89.8 mass
d) Slovenia	3			89 conc.
				89.8 mass
e) Sweden	3			92.7 conc.
	2			86.2 mass
16. Vymazal (2005)	2	18m² 2500m²	9.7 4.6	97 80±3.4

The metrics reporting issues mentioned for TSS are also present for BOD results. Steer states that his 21 systems met EPA standards 89% of the time (D. Steer et al., 2002). Steer did remove his outliers that likely had inadequate pre-treatment. Seven of the systems reported met EPA standards and six failed to meet standards. This is not powerful enough data to recommend EPA approval for BOD treatment.

3) Nitrogen

Table 8: Nitrogen Results

Author	Number CWs	Area or Flow	Removal mg/l (EPA 1.5 ammonia)	Removal Percentage
1. Axler (2001)	2	1)75m2 2)480m2	1) S:491/100 2) S:443/100 W:1265/100	1) 42 2)S:20 W:21
			S:48 W:45	20 21
2. Brix (1994)	104		10.2 Mean	
3. Cooper (2001)		5.6m2/PE	Amm N: 39.7 Kjeldahl N:0 Oxidized N:3.4	
4. Dahab (2001)	1	500m2	S:NH3N:13.7(2.1-23.2) NO3N:2.2(0.6-4) W:NH4N:15.3(8.6-17.8) NO3N:2.5(1.7-4.5)	30.4 43.9 14 30.4
5. Gasiunas		360m2	Total N:13.5±5.7	48
6. Geller	8	600-1300m2	Total N 27	98
7. Griffin		5m2/PE	Amm N 39.7 Total N 3.4	
8. Ham	1	16m2	TN S:93 ±35.47 W:108 ±36.18	20 ±28 7.7 ±12.91
9. Hench			TKN S:5.9 (SE2.1) W:5.6 (SE1.3)	
10. Merlin		350m2		TKN 57.3 ±21.2
11. Perfler		52.5m2	NH4N :39 Total N :47	48 49
12. Rousseau	2	896m2 & 1300m2		TN 33
13. Steer (2002)	21		NH3N:18.4 SD:16.7	56.5 SD:31.36
14. Steer (2005)	8		NH3N:9.14±1.23	NH3N: 70
				Met EPA <50% of the time
15. Vymazal (2002)	29-33		TN conc:27.1 SD:9 mass:15 SD:9	conc: 41.6 mass: 38.9
	35-37		Amm N conc:16.1 SD:9.1 mass:8.2 SD:6.3	conc:42.7 mass: 37.4
			Orgconc:2.87 SD:1.96	conc:64.8 mass:59.8
a) North America	12		TN: conc:8.4 mass:7.35	conc:55.6 mass: 44.3
	15-19		NH3 N conc:4.51 mass:6.4	conc:24.6 mass: 8.6
	11		Org N conc:4.03 mass:3.23	conc:60.1 mass:55.6

Table 8: Nitrogen Results

Author	Number CWs	Area or Flow	Removal mg/l (EPA 1.5 ammonia)	Removal Percentage
b) Germany	9		TN conc:59.8	conc: 48.0
c) Poland	6		TN conc:34.8 SD:21.6 mass:12.5 SD:6.4	conc: 24.5 mass:20.9
d) Slovenia	3		NH3N conc:7.7 SD:6.3 mass:3.9 SD:3.1	conc:73.2 mass: 74.1
e) Sweden	3		TN conc:15.1 SD:8.0 mass:8.7 SD:0.25	conc: 40.3 mass :44.9
16. Vymazal (2005)	2	1)18m2	NH4:51 NO2N:2.9 Organic N :1.1 TN:55	14 unknown 95 35
		2)2500m2	NH4N:9.4 SD:5.0 NO3N:1.79 SD:2.2	19 40
Legend:	ammonia:NH4 &NH3 N		nitrates:NO3 & NO2 N	

In addition to the variables affecting the TSS and BOD results, reporting of nitrogen degradation is even more confusing, as will be shown in the "discussion" section.

It is apparent that no discharging SSFCW can meet the OEPA standards. The literature review did find that the use of iron in the substrate allowed almost total removal of nitrogen species. This is an area for research in Ohio.

4) Phosphorus

Table 9: Phosphorus Results

Author	Number CWs	Area or Flow	Removal mg/l (EPA limit: 1)	Removal Percentage
1. Axler	2	1) 75m2 2)480m2	1) S:491/100 2) S:443/100 W:1265/100	51 20 30 15
2. Brix	104		5.9 Mean	
3. Cooper		5.6m2/PE		
4. Dahab	1	500m2	S:2.3 (0.6-4.5) W:2.2 (0.9-3)	21 12.6
5. Gasiunas		360m2	1.12±0.84	61
6. Geller	8	600-1300m2	0.8	98
7. Griffin		5m2/PE		
8. Ham	1	16m2	S:7.1±3.58 W:8.5±2.81	44 ±33.2 26.8 ±27.15
9. Hench				
10. Merlin		350m2		69.4±27.1
11. Perfler		52.5m2	2	1
12. Rousseau	2	896&1300m2		0
13. Steer (2002)	21		1.71 SD:2.41	80.5 SD:19.8 Met EPA 50% of the time
14. Steer (2005)	8		2.79±0.4	55
15. Vymazal (2002)	32 30		conc:3.22+-2.06 mass:1.76+-1.66	conc:51 mass :42.5
a) North America	8		conc:2.97 mass:4.0	conc: 32.7 mass: 22.2
b) Germany	26		conc:3.99	conc:65
c) Poland	5		conc:4.10+-1.45 mass:1.60+-0.64	conc: 46.4 mass 41.2
d) Slovenia				
e) Sweden	3		conc:2.10+-1.21 mass:1.56+-0.20	conc: 58.3 mass: 61.4
16. Vymazal (2005)	2	1)18m2 2)2500m2	1) 10.6 2) 2.04±1.52	38 7

All the authors use the same reporting system for phosphorus. Vymazal alone divides his results by effluent concentration and mass loading. One important factor not detailed in almost all of the articles is the iron makeup of the substrate. As was discussed in the literature review, the addition of iron increases the removal of both nitrogen and phosphorus to almost 100%. The lack of data on this confounding factor must be considered in analyzing all of the nitrogen and phosphorus results. It is apparent that none of these meets the rigid OEPA limit of 1mg/l. However, 11 of the reports give concentration levels under 4mg/l, apparently without iron. This gives hope for meeting the standards with iron substrate.

5) Fecal Coliforms

Table 10: Fecal Coliform Results

Author	Number CWs	Area or Flow	Colony counts/100ml (EPA,2000)	Removal Percentage
1. Axler	2	1) 75m2 2) 480m2	1) S:491/100 2) S:443/100 W:1265/100	mean99 99.7 98.9
2. Brix	104			
3. Cooper				
4. Dahab	1	500m2	S:18,800(<200-110,000) W:13,600(1700-50,000)	1.90 log reduction 1.78 log reduction
5. Gasiunas				
6. Geller				
7. Griffin				
8. Ham				
9. Hench			S:5.7(0.3) W:6.1(0.4)	
10. Merlin				99
11. Perfler				
12. Rousseau				
13. Steer (2002)	21	2-7 PE	2150 SD=5670	87.9 SD:27.16 Met EPA 74% of the time
14. Steer (2005)	8	2-7 PE	1248/100±326	99
15. Vymazal (2002)				
a) North America				
b) Germany				
c) Poland				
d) Slovenia				
e) Sweden				
16. Vymazal (2005)	2	18m2-2500m2	5.01±5.42	1

Only six authors give results for coliforms, and except for Dahab's one system, they all meet the EPA guidelines of <2000 counts/100ml (Dahab & Surampalli, 2001). Steer says that his 21 systems meet EPA standards 74% of the time (D. Steer et al., 2002). Some authors report treatment as log reduction instead of, or in addition to colony count. These pooled results confirm the literature review about the ability of SSFCWs to detoxify not only coliforms, but many other pathogens to meet EPA standards.

DISCUSSION

The Met-analytic procedure used by the author could be improved. Different topic searches could be used by the next researcher to see if more studies on small systems can be found. The lack of any articles from Canada, where CWs are used for sewage treatment, is of concern. Another limitation is the “file drawer” effect, where studies may not have been published because they did not demonstrate significant results. The Web of Science search engine would miss Masters and Doctorate projects that did not get published.

Looking at the charts of results for each of the five parameters, there are a number of apparent problems in attempting to perform a rigid statistical analysis. In the columns under number of CWs studied, the numbers vary from 1 or unknown to 104. Considering size, some are given as m^2 and vary from 16-4500; some are given as m^2/PE (5&5.6); others are given as PE treated and vary from 2-350. How can one take into account the actual number of CWs and the varying size contributing to each authors’ data? Some data is given as removal percentage, some as mg/l, and some as both. Some of these results are further subdivided by effluent concentration (mg/l) and by mass loading amounts (kg/hectare/day).

There are a number of other problems that are less apparent. Some studies have CWs with 1-4 beds in series or parallel (J. Vymazal, 2002). Some may have inadequate pre-treatment based on the high influent TSS (D. Steer et al., 2002). Others give no information on the number of cells or type of pre-treatment (Vymazal 2002 comparison data, Brix’ 104 systems). Perhaps the 2002 and 2005 data from Steer are the most helpful (D. Steer et al., 2002; D. Steer et al., 2005). These are from SSFCWs of single-family homes (PE2-7). He indicates that the systems met EPA standards 79% of the time (21, 2002 systems) and >95% of the time (eight, 2005 systems). This author does not believe that those results are sufficient to recommend full acceptance of the technology.

Many of the articles do not mention insulation, and since research has proven the importance of insulation, the comparisons may not be for similar wetland designs.

OEPA lists ammonia nitrogen as the discharge standard (1.5mg/l maximum). As can be seen by the results chart, however, data is variously reported as total nitrogen, Kjeldahl N, NH3, NH4, NO3, ammonia N, oxidized N, and organic N. Further, these are sometimes reported by effluent concentration, sometimes by mass loading, and sometimes by percent removal. Perhaps the nitrogen results more than any other cry out for the urgent need of some international or national agreement on how best to report the efficiency of CWs.

It is apparent that one cannot do a true Meta-analysis on the data collected from this particular search. This attempt at comparison represents a classic case of trying to compare apples to oranges and cannot be done using the method outlined above.

Based on the literature review, it appears that SSFCW technology, with the addition of iron to the medium should be sufficient to meet EPA guidelines for discharging systems. This could not be proven by a Meta-analysis. More research needs to be done on the design size for on-site systems to render them non-discharging, which would eliminate the need for adherence to EPA rules. The seven Logan County systems and the majority of systems reported by Steer do not discharge (Steer). The literature review and pooled results do show very good treatment of the wastewater stream by these wetlands. As such, they would be an excellent choice for secondary treatment before final discharge into a small ground absorption- based tile field for final treatment.

There is a particular problem with the reporting of results that make standard comparison techniques problematic. The authorities and researchers need to resolve this. One of the reasons for the discrepancy is that some countries consider the total load to the environment and so demand stricter effluent standards from large dischargers than from small systems. The NPDES rules in combination with TDML attempt to provide this guide, but essentially leave on-site systems with a mandate not to discharge. When replacement for failing systems becomes necessary, the expense for an approved system (mound) on lots with poor soils or high water tables becomes an unplanned financial burden to the homeowner. This paper has documented the significant percentage of systems that are failing in the USA.

One final issue that needs to be resolved is the definition of “failure”. There seems to be agreement that any system that discharges to the surface has failed, but it is unclear if each author has the same definition of “failure”, and equally unclear if the term means the same for each of the technologies used for home wastewater treatment.

CONCLUSIONS

The efficient treatment of sewage is problematic for small systems and single-family dwellings. Release of large quantities of pollutants from inadequately treated wastewater contaminates the environment and can be particularly devastating to groundwater, which is the main source of drinking water for most of the world. It can also seriously alter the vitality of streams and lakes. A significant percentage of domestic on-site systems are failing in Ohio.

There is a need for simplified technology for home wastewater treatment that meets the criteria set out in "*Introduction*". Much more research has been published on SSFCWs than on weeping tile beds or on any of the mechanical technologies currently used. SSFCWs are accepted technology in most of the world, but because they were originally designed to discharge, they remain "experimental" in Ohio.

In 1993, the USEPA identified the high priority research areas for CWs as: i) temperature and seasonal effects on wastewater treatment, ii) the role of plants in providing oxygen for root zone processes, and iii) the investigation of suitable plant species (US Environmental Protection Agency, 1993). This paper addresses those USEPA concerns.

The use of plants and insulation settle the first question about seasonal and temperature effects. The extensive discussion on nitrogen removal shows that science is very close to answering the second issue about plant effects on oxygen in root zone processes. It is proven that adding iron to the substrate improves the nitrogen and phosphorus degradation to almost 100%. More replicated research on the iron solution to P and N removal is necessary. Investigation is extensive in answering the third question about suitable plant species, and *Phragmites australis* is the obvious choice.

Axler and colleagues in their paper from Minnesota, concluded that “CWs are a viable, year-round treatment option for homeowners in terms of performance, ease of operation, and cost but require additional maintenance related to inconsistent vegetation growth, winter insulation, and meeting concentration-based regulatory standards since they are seasonally and annually variable due to rain events, partial freezing, spring snowmelt, and summer evaporation” (Axler et al., 2001). The updated research presented in this paper, particularly on the value of insulation, answers Axler’s concerns about inconsistent vegetation growth, insulation, and partial freezing. No authors have found any rain or melt problems in home systems that are constructed with a small berm to prevent water inflow from surrounding land and that are sealed to prevent water inflow from high water tables.

David Steer presented data from 21 single-family, three cell systems (septic tank with two wetlands) monitored over eight years in Ohio (D. Steer et al., 2002). He concludes that the systems were “found to meet USEPA effluent load guidelines in 68% of the quarterly water samples collected from 1994 to 2001”. However, in depth analysis of his own data found that specific units of the group accounted for many of the times when EPA guidelines were exceeded. He is unclear about the reasons for this finding. 68% is not an acceptable performance standard for EPA guidelines.

This paper demonstrates that horizontal subsurface flow constructed wetlands can be efficient in home wastewater treatment. They would be acceptable replacement technology for established homes with ground absorption-based systems failing in poor soils or high water tables. Experience in Logan County shows that when used as secondary treatment followed by a small ground absorption-based system, SSFCWs can provide on-site sewage treatment that does not discharge.

The author's conclusions on the status of SSFCWs and tile fields compared to the "ideal" HWTS is included in table form.

Table 11

STATUS OF HWTS TECHNOLOGY

IDEAL HWTS	**SSFCW**	**TILE BED**
It must not discharge to the ground, ditch or stream.	Fail (size matters)	Pass, but older failing
It must treat sewage to meet EPA standards if it does discharge.	Fail, but close (iron)	Fail
It must not use mechanical devices, except a pump designed to lift the sewage from the home to a higher elevation no more than once daily.	Pass	Pass
It must be energy independent, other than the possible initial use of a pump to lift sewage to the treatment area.	Pass	Pass
It should be simple & relatively inexpensive to build.	Pass	Pass
It must be easily understood by the homeowner	Pass	Pass

STATUS OF HWTS TECHNOLOGY

IDEAL HWTS	**SSFCW**	**TILE BED**
It must be simple and relatively inexpensive to maintain. This means pumping the tank once every 5 years, switching a valve between treatment devices no more than once a year, and changing pumps no more than once every 15 years.	**Pass**	**Pass**
It should be unaffected by soil type.	**Pass**	**Fail**
It should be functional in the presence of a high water table.	**Pass**	**Fail**
It should last the life of the house.	**?**	**?**
It should have a replacement area in case of failure.	**Unnecessary**	**Pass (lot size)**
It should have a small footprint on a one acre lot.	**Pass**	**Fail**

Based on the author's summary, CWs appear to have a place in home wastewater treatment.

An attempt at performing a Meta-analysis on pooled data uncovered a multitude of problems in the methods of measuring and reporting the five common parameters. There were a host of other difficulties. This author concludes that it is not possible to do a proper Meta-analysis due to the lack of standardization in measuring and reporting results.

POLICY IMPLICATIONS

Recommendation One: ODH and OEPA should approve horizontal subsurface flow constructed wetlands as secondary treatment for on-site systems prior to tertiary treatment by a small tile bed or other ground-based absorption system.

Recommendation Two: ODH and OEPA should approve horizontal subsurface flow constructed wetlands as replacement for failing systems in areas with high water tables or poor soils.

Recommendation Three: The Ohio Department of Health should set standards for reporting treatment results from CWs. ODH should serve as a repository for results from a statewide database of constructed wetlands. Particular attention should be paid to systems that do not discharge. There is a need for this database so that informed decisions can be made.

Recommendation Four: The USEPA and OEPA should reconsider whether effluent concentrations are the proper standard for discharge limits. The goal of the EPA to disallow all discharging systems is admirable, but if a high percent of older systems are failing, perhaps a replacement SSFCW system that is producing minimal quantities of effluent with good treatment effect should be allowed.

The use by the EPA of discharge concentrations to measure wastewater pollutants does not take into account the total load to the environment. Many other countries consider this load and so mandate higher standards for higher flow systems than they do for single dwellings. The EPA demands the same high standards of constructed wetlands that normally discharge small volumes of treated sewage as it does of municipal systems.

Recommendation Five: US researchers should promote a worldwide conference to standardize the method for determining parameter levels and the metrics for reporting treatment results. The author recommends that the following parameters be measured according to APHA 1995 standards: TSS, BOD^5, phosphorus, ammoniacal nitrogen, and coliforms count per 100 ml.

Recommendation Six: OEPA, ODH and university experts in Ohio should encourage and fund research on: i) the cheapest local method to obtain substrate with iron component and the treatment results of such a system ii) the ideal design for on-site SSFCW systems to assure that they do not discharge when used as secondary treatment. iii) the most efficient, economical design for export to developing countries.

Recommendation Seven: Design standards should be set by USEPA for SSFCWs. They should be two cells with total size of 10 m^2 per population equivalent when used as final treatment. They should be 5 m^2 per PE when used as secondary treatment prior to passing into a small tile field. The first cell must be lined but in areas where water table is not an issue the second cell of a two cell CW should be unlined. Number 10 pea gravel should be the substrate with larger gravel at the entrance and exit. One percent iron filings should be added to the substrate. Phragmites australis should be the macrophyte used and the cells should be insulated with ten inches of quality mulch.

APPENDICES

APPENDIX 1
VARIABLES NORMALLY MEASURED IN SEWAGE EFFLUENT

1) Total suspended solids (TSS)

Wastewater solids are categorized into several groups based on particle size and characterization. Most wastewaters are analyzed for one or several of the following types: total suspended solids (TSS), total dissolved solids (TDS), volatile suspended solids (VSS) and total solids (TS)

TSS is the amount of filterable solids in a water sample. Samples are filtered through a glass fiber filter. The filters are dried and weighed to determine the amount of total suspended solids in milligrams per liter (mg/l) of the sample.

2) Biological Oxygen Demand (BOD)

BOD refers to the amount of oxygen that would be consumed if all the organics in one liter of water were oxidized by bacteria and protozoa. It is often reported as BOD_5. It is a test of the concentration of biodegradable organic matter present in the sample. A BOD level of 1-2 ppm is considered normal. High concentrations of *dissolved oxygen* (DO) predict that oxygen uptake by microorganisms is low along with the required break down of nutrient sources in the medium (sample). On the other hand, low DO readings signify high oxygen demand from microorganisms, usually indicating pollution BOD is not an accurate quantitative test and takes five days to complete measurement. It is commonly reported in mg/l.

On occasion COD (chemical oxygen demand) is reported along with BOD. This test indirectly measures the amount of organic compounds in water. It is reported in mg/l

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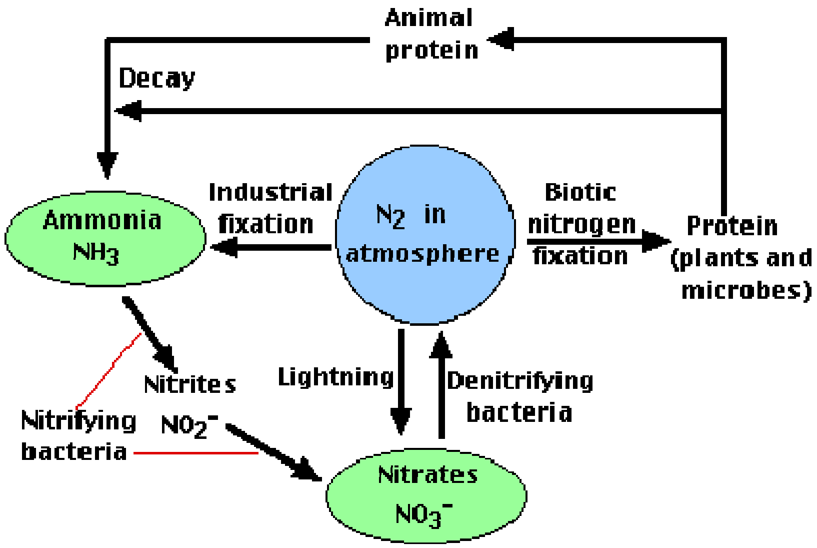
3) Nitrogen

This is usually reported as total nitrogen. In the degradation process, the nitrogen released into the atmosphere as ammonia (NH3) or N2 is not normally measured. Other nitrogen species produced in wetlands include nitrates and nitrites (NO2 & NO3). Some authors do report NH3 or N2. Measurement is usually done by calorimeter or chromatograph. Again, this is usually reported in mg/l.

The removal of ammonium is largely dependent on the oxygen supply. The macrophyte transports oxygen to the rhizosphere immediately surrounding the root, thus creating an aerobic microsite in a system that is otherwise anaerobic. In these aerobic areas ammonium ions are oxidized by nitrifying bacteria to nitrite, and then by nitrobacter to nitrate. In the anaerobic area further from the root, nitrate will be denitrified and emitted to the atmosphere as gaseous nitrogen (Brix, H., 1994))

Figure 6: The Nitrogen Cycle



4) Phosphorus

All authors agree that most of the removal of phosphorus occurs through adsorption by the media and substrate, and hence all SSFCWs have a finite capacity to remove P. Drizo did prove that selection of iron rich substrate (shale) in a phragmites wetland allowed the plant to become an important player in $H_2PO_4^-$ removal ((Drizo, 1997). Phosphorus removal is important because it is the nutrient most responsible for eutrofication limiting plant growth in streams and lakes.

Luderitz states that “the complexity of P compounds and their solubility makes most extraction methods in the literature difficult to interpret. According to the best information available, an exact stochiometric and structural identification and quantification of inorganic P species is very complicated” (Luderitz, V., & Gerlach, F., 2002). It is reported in mg/l.

5) Biological (coliform bacteria, viruses, parasites, etc)

Standardized detection methods are used for E. coli and coliform counts, the usual parameters that are measured in bathing water. Most standards require coliform counts of less than 2000 colonies per 100 ml (refer to Table 1: EPA surface discharge limits). The standardized testing method is well proven and used in many areas of science.

APPENDIX 2
CULMINATING EXPERIENCE COMPETENCIES

Many competencies were needed or learned during this project. The author had to recognize the wastewater treatment problem and how it was a public health issue affecting the American public. It was then necessary to research the extent of the problem and possible solutions. Skills in using search engines, evaluating literature, and organizing data were essential.

Further skills were necessary to understand the political and market forces bearing on the issue. Finally, presentation and communication skills were essential to advocate for public health properly. The areas identified are listed below.

Essential Service #1:
Monitor health status to identify community health problems

Analytic/Assessment Skills

- Defines a problem
- Identifies relevant and appropriate data and information sources
- Evaluates the integrity and comparability of data and identifies gaps in data sources
- Makes relevant inferences from quantitative and qualitative data

Leadership and Systems Thinking Skills

- Identifies internal and external issues that may impact delivery of essential public health services (i.e. strategic planning)

Essential Service #2:
Diagnose and investigate health problems and health hazards in the community

Analytic/Assessment Skills

- Defines a problem
- Identifies relevant and appropriate data and information sources
- Evaluates the integrity and comparability of data and identifies gaps in data sources
- Makes relevant inferences from quantitative and qualitative data

Communication Skills

- Effectively presents accurate demographic, statistical, programmatic, and scientific information for professional and lay audiences

Basic Public Health Sciences Skills

- Applies the basic public health sciences including behavioral and social sciences, biostatistics, epidemiology, environmental public health, and prevention of chronic and infectious diseases and injuries

Essential Service #3:

Inform, educate, and empower people about health issues

Policy Development/Program Planning Skills

- Collects, summarizes, and interprets information relevant to an issue
- States policy options and writes clear and concise policy statements
- Identifies, interprets, and implements public health laws, regulations, and policies related to specific programs

Essential Service #4:

Mobilize community partnerships to identify and solve health problems

Communication Skills

- Advocates for public health programs and resources
- Leads and participates in groups to address specific issues
- Effectively presents accurate demographic, statistical, programmatic, and scientific information for professional and lay audiences

Essential Service #10:

Research for new insights and innovative solutions to health problems

Analytic/Assessment Skills

- Defines a problem

Development/Program Planning Skills

- Collects, summarizes, and interprets information relevant to an issue
- Decides on the appropriate course of action

Basic Public Health Sciences Skills

- Identifies and retrieves current relevant scientific evidence
- Identifies the limitations of research and the importance of observations and interrelationships

REFERENCES

"Moeller, D. W. (2005). In Dade W. Moeller (Ed.), *Environmental health* (Third Edition). Cambridge, Massachusetts: Harvard University Press.

Allen, W. C., Hook, P. B., Biederman, J. A., & Stein, O. R. (2002). Temperature and wetland plant species effects on wastewater treatment and root zone oxidation. *Journal of Environmental Quality, 31*(3), 1010-1016.

Al-Omari, A., & Fayyad, M. (2003). Treatment of domestic wastewater by subsurface flow constructed wetlands in Jordan. *Desalination, 155*(1), 27-39.

American Public Health Association. (1995). *Standard methods for the examination of water and wastewater* (19th ed.). Washington, D.C.: American Public Health Association Inc.

Axler, R., Henneck, J., & McCarthy, B. (2001). Residential subsurface flow treatment wetlands in northern Minnesota. *Water Science and Technology, 44*(11-12), 345-352.

Barrett, E. C., Sobsey, M. D., House, C. H., & White, K. D. (2001). Microbial indicator removal in onsite constructed wetlands for wastewater treatment in the southeastern U.S. *Water Science and Technology : A Journal of the International Association on Water Pollution Research, 44*(11-12), 177-182.

Bayley, M. L., Davison, L., & Headley, T. R. (2003). Nitrogen removal from domestic effluent using subsurface flow constructed wetlands: Influence of depth, hydraulic residence time and pre-nitrification. *Water Science and Technology : A Journal of the International Association on Water Pollution Research, 48*(5), 175-182.

Begg, J. S., Lavigne, R. L., & Veneman, P. L. (2001). Reed beds: Constructed wetlands for municipal wastewater treatment plant sludge dewatering. *Water Science and Technology : A Journal of the International Association on Water Pollution Research, 44*(11-12), 393-398.

Bhamidimarri, R., Shilton, A., Armstrong, I., Jacobson, P., & Scarlett, D. (1991). Constructed wetlands for wastewater treatment-the New Zealand experience. *Water Science and Technology, 24*(5), 247-253.

Brix, H., & Arias, C. A. (2005). Danish guidelines for small-scale constructed wetland systems for onsite treatment of domestic sewage. *Water Science and Technology, 51*(9), 1-9.

Brix, H. (1994). Use of constructed wetlands in water-pollution control - historical development, present status, and future perspectives. *Water Science and Technology, 30*(8), 209-223.

Brix, H., Arias, C. A., & del Bubba, M. (2001). Media selection for sustainable phosphorus removal in subsurface flow constructed wetlands. *Water Science and Technology : A Journal of the International Association on Water Pollution Research, 44*(11-12), 47-54.

Brown, D. S., & Reed, S. C. (1994). Inventory of constructed wetlands in the united-states. *Water Science and Technology, 29*(4), 309-318.

Carpenter, S. R., Caraco, N. F., Correll, D. F., Howarth, R. W., Sharpley, A. N., & Smith, V. H. (1998). Nonpoint pollution of surface waters with nitrogen and phosphorus. *Ecological Applications, 8*(3), 559-568.

City of Austin-Onsite Treatment (Pretreatment) System Fact Sheets. (Retrieved February 3, 2006). *Septic tank to subsurface wetland system* No. XII Costs)

Conte, G., Martinuzzi, N., Giovannelli, L., Pucci, B., & Masi, F. (2001). Constructed wetlands for wastewater treatment in central Italy. *Water Science and Technology, 44*(11-12), 339-343.

Cooper, P. (2001). Constructed wetlands and reed-beds: Mature technology for the treatment of wastewater from small populations. *Journal of the Chartered Institution of Water and Environmental Management, 15*(2), 79-85.

Cooper, P., Willoughby, N., & Cooper, D. (2004). The use of reed-beds for sludge drying. *Water and Environment Journal, 18*(2), 85-89.

Dahab, M. F., & Surampalli, R. Y. (2001). Subsurface flow constructed wetlands treatment in the plains: Five years of experience. *Water Science and Technology : A Journal of the International Association on Water Pollution Research, 44*(11-12), 375-380.

Dahab, M. F., Surampalli, R. Y., & Liu, W. (2001). Performance modeling of subsurface-flow constructed wetlands systems. *Water Science and Technology, 44*(11-12), 231-235.

Davison, L., Headley, T., & Pratt, K. (2005). Aspects of design, structure, performance and operation of reed beds-eight years' experience in northeastern New South Wales, Australia. *Water Science and Technology : A Journal of the International Association on Water Pollution Research, 51*(10), 129-138.

Drizo, A., Frost, C. A., Grace, J., & Smith, K. A. (1999). Physico-chemical screening of phosphate-removing substrates for use in constructed wetland systems. *Water Research, 33*(17), 3595-3602.

Drizo, A., Frost, C. A., Smith, K. A., & Grace, J. (1997). Phosphate and ammonium removal by constructed wetlands with horizontal subsurface flow, using shale as a substrate. *Water Science and Technology, 35*(5), 95-102.

Forbes, M. G., Dickson, K. L., Saleh, F., Waller, W. T., Doyle, R. D., & Hudak, P. (2005). Recovery and fractionation of phosphorus retained by lightweight expanded shale and masonry sand used as media in subsurface flow treatment wetlands. *Environmental Science & Technology, 39*(12), 4621-4627.

Garcia, J., Aquirre, P., Barragan, J., Mujeriego, R., Matamoros, V., & Bayona, J. (2005). Effect of key design parameters on the efficiency of horizontal subsurface flow constructed wetlands. *Ecological Engineering, 25*(4), 405-418.

Garcia, J., Aguirre, P., Mujeriego, R., Huang, Y., Ortiz, L., & Bayona, J. M. (2004). Initial contaminant removal performance factors in horizontal flow reed beds used for treating urban wastewater. *Water Research, 38*(7), 1669-1678.

Gasiunas, V., Strusevicius, Z., & Struseviciene, M. (2005). Pollutant removal by horizontal subsurface flow constructed wetlands in Lithuania. *Journal of Environmental Science and Health, 40*, 1467-1477.

Geller, G. (1997). Horizontal subsurface flow systems in the German speaking countries: Summary of long-term scientific and practical experiences; recommendations. *Water Science and Technology, 35*(5), 157-166.

Giaever, H. M. (2000). Treatment performance of a multistage constructed wetland at 69 degrees north, Norway. *Journal of Environmental Science and Health Part A-Toxic/hazardous Substances & Environmental Engineering, 35*(8), 1377-1388.

Griffin, P. (2003). Ten years experience of treating all flows from combined sewerage systems using package plant and constructed wetland combinations. *Water Science and Technology, 48*(11-12), 93-99.

Griffin, P., & Pamplin, C. (1998). The advantages of a constructed reed bed based strategy for small sewage treatment works. *Water Science and Technology, 38*(3), 143-150.

Griffin, P., & Upton, J. (1999). Constructed wetlands: A strategy for sustainable wastewater treatment at small treatment works. *Journal of the Chartered Institution of Water and Environmental Management, 13*(6), 441-446.

Gschlossl, T., & Stuible, H. (2000). Reed bed systems: Design, performance and maintainability. *Water Science and Technology, 41*(1), 73-76.

Ham, J. H., Yoon, C. G., Hwang, S. J., & Jung, K. W. (2004). Seasonal performance of constructed wetland and winter storage pond for sewage treatment in Korea. *Journal of Environmental Science and Health Part A-Toxic/hazardous Substances & Environmental Engineering, 39*(5), 1329-1343.

Hench, K. R., Sexstone, A. J., & Bissonnette, G. K. (2004). Heterotrophic community-level physiological profiles of domestic wastewater following treatment by small constructed subsurface flow wetlands. *Water Environment Research, 76*(5), 468-473.

Jenssen, P. D., Maehlum, T., & Krogstad, T. (1993). Potential use of constructed wetlands for waste-water treatment in northern environments. *Water Science and Technology, 28*(10), 149-157.

Kadlec, R. H., & Reddy, K. R. (2001). Temperature effects in treatment wetlands. *Water Environment Research, 73*(5), 543-557.

Kurtenbach, E. (2005, December 28). China: Government says 300 million rural residents drink unsafe water, as worries mount over pollution. [Electronic version]. *Associated Press in Epi-X Media Tracking Report, December 29, 2005,* pp. 6-7.

Kuschk, P., Wiebner, A., Kappelmeyer, U., Weibrodt, E., Kastner, M., & Stottmeister, U. (2003). Annual cycle of nitrogen removal by a pilot-scale subsurface horizontal flow in a constructed wetland under moderate climate. *Water Research, 37,* 4236-4242.

Lakatos, G., Kiss, M. K., Kiss, M., & Juhasz, P. (1997). Application of constructed wetlands for wastewater treatment in Hungary. *Water Science and Technology, 35*(5), 331-336.

Langergraber, G., & Haberl, R. (2001). Constructed wetlands for water treatment. *Minerva Biotecnologica, 13*(2), 123-134.

Li, X. F., & Chuncai, J. (1995). Constructed wetland systems for water pollution control in north china. *Water Science and Technology, 32*(3), 349-356.

Luderitz, V., & Gerlach, F. (2002). Phosphorus removal in different constructed wetlands. *Acta Biotechnologica, 22*(1-2), 91-99.

Luederitz, V., Eckert, E., Lange-Weber, M., Lange, A., & Gersberg, R. (2001). Nutrient removal efficiency and resource economics of vertical flow and horizontal flow constructed wetlands. *Ecological Engineering, 18*, 157-171.

Maehlum, T., & Stalnacke, P. (1999). Removal efficiency of three cold-climate constructed wetlands treating domestic wastewater: Effects of temperature, seasons, loading rates and input concentrations. *Water Science Technology, 40*(3), 273-281.

Maehlum, T., Jenssen, P. D., & Warner, W. S. (1995). Cold-climate constructed wetlands. *Water Science and Technology, 32*(3), 95-101.

Mander, U., Kuusemets, V., Lohmus, K., Mauring, T., Teiter, S., & Augustin, J. (2003). Nitrous oxide, dinitrogen and methane emission in a subsurface flow constructed wetland. *Water Science and Technology : A Journal of the International Association on Water Pollution Research, 48*(5), 135-142.

Merlin, G., Pajean, J. L., & Lissolo, T. (2002). Performances of constructed wetlands for municipal wastewater treatment in rural mountainous area. *Hydrobiologia, 469*(1-3), 87-98.

Mitsch, W. J., & Gosselink, J. G. (2000). *Wetlands* (3rd ed.). New York: Wiley.

Munch, C., Kuschk, P., & Roske, I. (2005). Root stimulated nitrogen removal: Only a local effect or important for water treatment? *Water Science and Technology : A Journal of the International Association on Water Pollution Research, 51*(9), 185-192.

Ohio Environmental Protection Agency. (2001b). *Ohio environmental protection agency general permit authorization to discharge wastewater from new and replacement household sewage treatment systems under the national pollutant discharge elimination system*. Columbus, OH: OEPA.

Ohio Environmental Protection Agency. (1999a). *Ohio environmental protection agency general permit authorization to discharge wastewater from sewage treatment systems designed to treat an average of 25,000 gallons per day or less under the national pollution discharge elimination system*. Columbus, OH: OEPA.

Ohio State University Extension. *AEX-740 septic system maintenance.* Retrieved 05/18, 2006 from http://ohioline.osu.edu/aex-fact/0740.html

Perfler, R., & Haberl, R. (1993). Actual experiences with the use of reed bed systems for waste-water treatment in single households. *Water Science and Technology, 28*(10), 141-148.

Philippi, L. S., da Costa, R. H. R., & Sezerino, P. H. (1999). Domestic effluent treatment through integrated system of septic tank and root zone. *Water Science and Technology, 40*(3), 125-131.

Picard, C. R., Fraser, L. H., & Steer, D. (2005). The interacting effects of temperature and plant community type on nutrient removal in wetland microcosms. *Bioresource Technology, 96*(9), 1039-1047.

Quinonez-Diaz, M. J., Karpiscak, M. M., Ellman, E. D., & Gerba, C. P. (2001). Removal of pathogenic and indicator microorganisms by a constructed wetland receiving untreated domestic wastewater. *J.Environ.Sci.Health.A.Tox.Hazard.Subst.Environ.Eng., 36*(7), 1311-1320.

Reed, S. C., & Brown, D. (1995). Subsurface flow wetlands - a performance evaluation. *Water Environment Research, 67*(2), 244-248.

Richter, A. Y., & Weaver, R. W. (2003). Treatment of domestic wastewater by subsurface flow constructed wetlands filled with gravel and tire chip media. *Environmental Technology, 24*(12), 1561-1567.

Rosenthal, R. (1991). In Rosenthal R. (Ed.), *Meta-analytic procedures for social research* (Revised ed.). London, England: Sage Publications Ltd.

Rousseau, D. P. L., Vanrolleghem, P. A., & De Pauw, N. (2004). Constructed wetlands in Flanders: A performance analysis. *Ecological Engineering, 23*(3), 151-163.

Seidel, K., Happel, H., & Grau, G. (1978). Contributions to revitalisation of waters. In K. Seidel, & V. Krefeld (Eds.), (2 ed.) (pp. 1-62). Germany: Stiftung Limnologische Arbeititsgruppe.

Solano, M. L., Soriano, P., & Ciria, M. P. (2004). Constructed wetlands as a sustainable solution for wastewater treatment in small villages. *Biosystems Engineering, 87*(1), 109-118.

Srinivasan, N., Weaver, R. W., Lesikar, B. J., & Persyn, R. A. (2000). Improvement of domestic wastewater quality by subsurface flow constructed wetlands. *Bioresource Technology, 75*(1), 19-25.

Steer, D., Fraser, L., Boddy, J., & Seibert, B. (2002). Efficiency of small constructed wetlands for subsurface treatment of single-family domestic effluent. *Ecological Engineering, 18,* 429-440.

Steer, D., Fraser, L., & Seibert, B. (2005). Cell-to-cell pollution reduction effectiveness of subsurface domestic treatment wetlands. *Bioresource Technology, 96*(8), 969-976.

Stott, R., May, E., Matsushita, E., & Warren, A. (2001). Protozoan predation as a mechanism for the removal of cryptosporidium oocysts from wastewaters in constructed wetlands. *Water Sci. Technol, 44*(No 11-12), pp 191-198.

Stottmeister, U., Wiessner, A., Kuschk, P., Kappelmeyer, U., Kastner, M., & Bederski, O. et al. (2003). Effects of plants and microorganisms in constructed wetlands for wastewater treatment. *Biotechnology Advances, 22*(1-2), 93-117.

Tanner, C. C., & Kadlec, R. H. (2003). Oxygen flux implications of observed nitrogen removal rates in subsurface flow treatment wetlands. *Water Science and Technology : A Journal of the International Association on Water Pollution Research, 48*(5), 191-198.

Tanner, C. C., Kadlec, R. H., Gibbs, M. M., Sukias, J. P. S., & Nguyen, M. L. (2002). Nitrogen processing gradients in subsurface-flow treatment wetlands-influence of wastewater characteristics. *Ecological Engineering, 18,* 499-520.

U.S. Environmental Protection Agency. (1980). *Design manual: Onsite wastewater treatment and disposal systems* No. EPA 625/1-80-012) U.S. Environmental Protection Agency.

US Environmental Protection Agency. (2001b). *Protection of the nation's waters through effective NPDES permits: A strategic plan.* Washington, DC:

US Environmental Protection Agency. (1998). *National water quality inventory: 1998 report to congress* No. report EPA 305(b)). Washington, DC: US Environmental Protection Agency.

US Environmental Protection Agency. (1997). *Response to congress on use of decentralized wastewater treatment systems*. Washington, DC: United States Environmental Protection Agency Office of Water & Office of Wastewater Managemant.

US Environmental Protection Agency. (1993). *Subsurface flow constructed wetlands for wastewater treatment: A technology assessment* No. EPA/832/R/93/001). Washington, DC: USEPA, Office of Water.

Vanier, S. M., & Dahab, M. F. (2001). Start-up performance of a subsurface flow constructed wetland for domestic wastewater treatment. *Environmental Technology, 22*(5), 587-596.

Various, 7th International Conference on Wetland systems. (2001). Selected proceedings of the 7th international conference on wetland systems for water pollution control 2000, held in Lake Buena Vista, Florida, USA. *Water Science & Technology, 44*(11-12), 1-614.

Vymazal, J. (2002). The use of subsurface constructed wetlands for wastewater treatment in the Czech Republic: 10 years experience. *Ecological Engineering, 18*(5), 633-646.

Vymazal, J. (2005). Horizontal sub-surface flow and hybrid constructed wetlands systems for wastewater treatment. *Ecological Engineering, 25*(5), 478-490.

Vymazal, J., Balcarova, J., & Dousova, H. (2001a). Bacterial dynamics in the subsurface constructed wetland. *Water Science and Technology : A Journal of the International Association on Water Pollution Research, 44*(11-12), 207-209.

Wallace, S., Parkin, G., & Cross, C. (2001). Cold climate wetlands: Design and performance. *Water Science and Technology : A Journal of the International Association on Water Pollution Research, 44*(11-12), 259-265.

Wetzel, R. G. (2001). Fundamental processes within natural and constructed wetland ecosystems: Short-term versus long-term objectives. *Water Science and Technology : A Journal of the International Association on Water Pollution Research, 44*(11-12), 1-8.

Wittgren, H. B., & Maehlum, T. (1997). Wastewater treatment wetlands in cold climates. *Water Science and Technology, 35*(5), 45-53.

Yoon, C. G., Kwun, S. K., & Ham, J. H. (2001). Feasibility study of a constructed wetland for sewage treatment in a Korean rural community. *Journal of Environmental Science and Health Part A-Toxic/hazardous Substances & Environmental Engineering, 36*(6), 1101-1112.