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# Small-Scale Constructed Wetland Treatment Systems
## Feasibility, Design Criteria, and O&M Requirements

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# SMALL-SCALE CONSTRUCTED WETLAND TREATMENT SYSTEMS

## FEASIBILITY, DESIGN CRITERIA, AND O&M REQUIREMENTS

**by:**

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***2006***

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# ABSTRACT AND BENEFITS

**Abstract:**

The expanding use of decentralized wastewater management has resulted in an increased interest in small-scale wetland treatment systems. However, there is limited information available on the use, distribution of, and performance of these wastewater treatment systems. The purpose of this study was to address this knowledge gap by developing criteria for the feasibility, design, operation, and maintenance of small-scale wetland systems.

A total of 1640 small-scale treatment wetlands was identified as part of the data collection effort for this project. The data obtained came from a variety of wetlands with different design parameters, loading rates, and geographic locations. The data was used to develop sizing criteria for the two most common types of small-scale treatment wetlands: free water surface (FWS) wetlands and vegetated submerged bed (VSB) wetlands for removal of the following wastewater constituents: biochemical oxygen demand (BOD), total suspended solids (TSS), total Kjeldahl nitrogen (TKN), total phosphorus (TP).

In addition to the sizing criteria, this manual provides basic information on wastewater generation, the feasibility of wetland technology, and internal treatment processes in constructed wetlands. Important design issues such as hydraulic considerations, cold-climate performance, operations and maintenance, vegetation establishment, and construction costs are also presented in this report.

**Benefits:**

- Describes the feasibility of small-scale constructed wetland technology.
- Evaluates the use, distribution, and performance of small-scale constructed wetlands.
- Presents a comprehensive review of the state of understanding in wetland treatment processes, with detailed charts and illustrations of internal processes that will facilitate wetland design and operation.
- Presents design criteria based on the actual performance of existing small-scale wetland systems.
- Provides guidance for evaluating the conservativeness of a wetland design.
- Provides guidance for wetland plant selection and establishment.
- Describes key procedures for operation and maintenance of wetland treatment systems.

**Keywords:** treatment wetland, FWS wetland, VSB wetland, design, operation and maintenance, decentralized wastewater management

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| | |
|---|---|
| AMD | Acid Mine Drainage |
| BOD | Biochemical Oxygen Demand |
| BOD$_5$ | 5-day Biochemical Oxygen Demand |
| BOD$_u$ | Ultimate Biochemical Oxygen Demand |
| BTEX | Benzene-Toluene-Ethylbenzene-Xylene |
| Bti | *Bacillus thuringiensis* variety *israelensis* |
| CBOD$_5$ | Carbonaceous 5-day Biochemical Oxygen Demand |
| CEC | Cation Exchange Capacity |
| CFU | Colony Forming Unit |
| COD | Chemical Oxygen Demand |
| CSTR | Continuously Stirred Tank Reactor |
| DO | Dissolved Oxygen |
| DOC | Dissolved Oxygen Carbon |
| EC/EWPCA | European Community/European Water Pollution Control Association |
| ENR CCI | Engineering News Record Construction Cost Index |
| EP | Pan Evaporation |
| ET | Evapotranspiration |
| FAC | Facultative |
| FACU | Facultative Upland |
| FACW | Facultative Wetland |
| FC | Fecal Coliform |
| FISH | Fluorescent In-Situ Hybridization |
| FWS | Free Water Surface |
| GFA | Gesellschaft zur Föderung der Abwassertechnik |
| GPD | gallons per day |
| GRO | Gasoline Range Organics |
| Ha | hectare |
| HDPE | High Density Polyethylene |
| HRT | Hydraulic Retention Time |
| IWA | International Water Association |
| LECA | Light Expanded Clay Aggregate |
| LLDPE | Linear Low-Density Polyethylene |
| L:H | Length-to-Height |
| L:W | Length-to-Width |
| MPIP | Max Planck Institute Process |
| MTBE | Methyl *tert*-Butyl Ether |
| NABD | North American Treatment Wetland Database |
| NASA | National Aeronautics and Space Administration |
| OBL | Obligate |
| ÖNORM | Österreichisches Normunginstitut |
| O&M | Operation and Maintenance |
| PE | Population Equivalent |
| PFR | Plug Flow Reactor |
| PVC | Polyvinyl Chloride |
| SAV | Submerged Aquatic Vegetation |
| TIS | Tanks-in-Series |

| | |
|---|---|
| TKN | Total Kjeldahl Nitrogen |
| TN | Total Nitrogen |
| TPH | Total Petroleum Hydrocarbons |
| TP | Total Phosphorus |
| TSS | Total Suspended Solids |
| TVA | Tennessee Valley Authority |
| U.K. | United Kingdom |
| UPL | Upland |
| U.S. | United States |
| USD | United States Dollars |
| USPHS | United States Public Health Service |
| UV | Ultraviolet |
| VF | Vertical Flow |
| VIP | Ventilated Improved Pit |
| VSB | Vegetated Submerged Bed |
| WERF | Water Environment Research Foundation |

# EXECUTIVE SUMMARY

The use of constructed wetlands for treatment of domestic wastewater has increased exponentially in the past decade, especially for small-scale applications such as individual homes and small communities. Despite the abundant use of wetland technology at this scale, the majority of small wetland systems are permitted at the local level and fall below state or provincial permitting thresholds, making them difficult to locate. Moreover, performance monitoring and reporting requirements for small-scale systems varies widely by geographic location. As a result, there is no central source of information on small-scale wetland systems. Small-scale wetland designs are often based on best professional judgment or borrowed design equations from other treatment technologies, such as facultative lagoons.

The purpose of this study was to provide guidance for the designers and operators of such small-scale wetland systems. This report discusses the feasibility of constructed wetland technology (Chapter 1.0); identifies wetland technologies that are appropriate for small-scale treatment systems (Chapter 2.0); evaluates the use, distribution, and performance of small-scale wetlands identified in this study (Chapter 3.0); reviews the state of understanding in wetland treatment processes (Chapter 4.0); provides information on removal mechanisms and design guidance particular to free water surface (FWS) wetlands (Chapters 5.0 and 7.0) and vegetated submerged bed (VSB) wetlands (Chapters 6.0 and 8.0); presents information on wetland plant selection and establishment (Chapter 9.0), operations and maintenance (Chapter 10.0), cost (Chapter 11.0); and ends with a discussion on special applications of wetland technology (Chapter 12.0).

The data collection effort of this study resulted in the identification of 1,640 wetland systems meeting the size (6 ha) and flow (2,000 $m^3/d$) threshold to be considered small-scale. Of the wetlands identified in this study, only 6% overlap with those reported in the North American Treatment Wetland Database (U.S. EPA, 1997b). Approximately 23% of the 1,640 systems reported treat wastewater from individual homes (2.6 $m^3/d$ or less), and 89% of the systems reported serve populations of 5,000 people or fewer (1000 $m^3/d$). The vast majority of wetland systems reported (93%) were VSB wetlands. Because VSB wetlands do not have an open water surface, exposure to pathogens is minimized. This attribute encourages preferential use of this technology for individual homes and small communities.

This report also provides guidance on the two most crucial aspects of small-scale wetland design: hydraulics and pollutant removal. Hydraulic considerations for VSB wetlands are discussed in detail. Areal loading charts for pollutant removal in FWS and VSB wetlands were developed for common wastewater constituents (biochemical oxygen demand, total suspended solids, total Kjeldahl nitrogen, and total phosphorus) based on first-order pollutant removal rates and non-zero background concentrations.

# CHAPTER 1.0

# INTRODUCTION

How do small-scale wastewater projects differ from large ones?

In private practice, engineers quickly realize that small-project design can be much more challenging than large-project design. Issues that arise during the large-project design process (technology selection, site planning, specifications, cost estimates, etc.) also arise in the design of small projects. Addressing all of these design issues in small projects can be difficult because they often have limited resources and budgets.

Small wastewater projects also differ from large projects in regards to operations and maintenance. Unlike larger, more conventional systems, small projects cannot afford the services of a full-time, dedicated operations and maintenance (O&M) staff. Most small-scale systems rely on periodic visits by a system operator; often funding allows an operator to visit a site just once or twice a month. Even then, the operator budget may limit system visits to a few hours at a time. Small treatment systems are held to the same effluent standards as large treatment works, and must be simple and robust in order to operate continually with minimal attention. Given this situation, the appropriate technology for small-scale treatment works must:

- Produce a consistent effluent quality despite variable flow and loading.
- Operate without constant tweaking and adjustment.
- Minimize the use of mechanical equipment because equipment can break often or malfunction between operator visits).
- Be constructed out of local materials (especially in developing countries).

Due to these factors, there is an increasing interest in the use of constructed wetlands in the field of decentralized wastewater management (U.S. EPA, 1997a). Wetlands are simple treatment systems that mainly rely on passive treatment processes. From a public perspective, they are an environmentally responsible treatment process.

Although wetland technology has been studied since 1952 (Seidel, 1973) and has been in full-scale operation since 1974 (Kickuth, 1977), our understanding of wetland treatment processes is still evolving. New applications of wetland technology are still being developed.

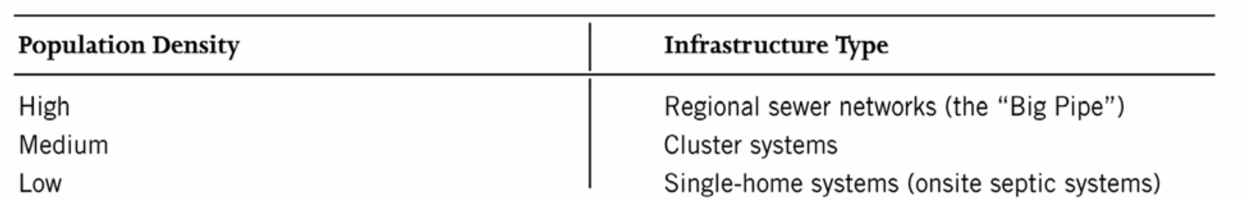
The current state-of-the-art design approaches can be characterized as *semi-empirical* (partly quantitative and partly empirical). For large wetland treatment systems, designers typically use a quantitative method to determine the overall size of a system (Kadlec and Knight, 1996; U.S. EPA, 2000a). However, current designers of small-scale systems lack the quantitative design information that is available for larger systems. Small-scale wetland treatment systems are often sized on best judgment or by using equations borrowed from other treatment technologies, such as facultative lagoons.

The goal of this manual is to provide effective tools for the design, operation, and maintenance of small-scale wetland treatment systems. Due to the unique factors that must be considered in decentralized wastewater management, engineers need simple, yet robust tools for designing wetland treatment systems.

## 1.1 Wastewater Management

The concept of decentralized wastewater management arises from a realization that conventional, large-scale treatment works cannot cost-effectively solve the wastewater management problems in areas of low population density and/or low capital investment (U.S. EPA, 1997a). There are three basic models of wastewater infrastructure (Hallahan and Wallace, 2001), as shown in Table 1-1.

Table 1-1. Wastewater Infrastructure Models.
Adapted from Hallahan and Wallace, 2001.



| Population Density | Infrastructure Type |
|---|---|
| High | Regional sewer networks (the "Big Pipe") |
| Medium | Cluster systems |
| Low | Single-home systems (onsite septic systems) |

### 1.1.1 Regional Sewer Networks ("The Big Pipe")

Building sewers to transport waste away from urban areas is an ancient practice. The practice of building sewers in urban areas dates back to 7,000 BC (Bertrand-Krajewski, 2003). The great sewer of Rome, the Cloaca Maxima, was built around 550–500 BC (Smith, 1875). In many large urban areas, wastes were often deposited into cesspools and vaults. This material was often removed by scavengers or farmers and applied to nearby farm fields. In the mid 1800s, eight U.S. cities (including New York, Baltimore, Cleveland, and Washington, D.C.) sold their night soil to processors who made it into fertilizer (Del Porto and Steinfeld, 2000). As water distribution systems were installed in urban areas, the use of flush toilets gained popularity and dramatically increased the volume of wastewater discharged to the cesspools. This resulted in overflows and increased maintenance costs, and citizens soon began to demand better sanitary conditions. This led to the development of regional sewer networks capable of carrying the sewage away from the population centers.

In developed countries, the conventional engineering focus has been to design wastewater infrastructure based on the regional (Big Pipe) model. This model is generally characterized by gravity sewers, activated sludge or trickling filter treatment, and surface water outfalls. In the United States, the Clean Water Act of 1972 provided funding to construct wastewater treatment plants under the regional infrastructure model. The objective was to provide secondary (biological) treatment of wastewater. Between 1972 and 1996, the number of people in the United States served by secondary or advanced wastewater treatment systems increased from 85 to 173 million (Fox, 1999). Since grant and loan dollars were allocated based on need, and need was determined in part by the number of people served, the majority of financial assistance went to large metropolitan areas.

Cost estimates to continue building regional infrastructure capable of addressing the wastewater needs in the United States range between $200 and $330 billion U.S. dollars (USD) (Fox, 1999). Between 1972 and 1996, the United States invested approximately $70 billion USD in wastewater infrastructure (Fox, 1999). The funding required to continue building wastewater infrastructure under this paradigm is economically infeasible. To address this problem, other infrastructure models such as cluster and single-home systems must be considered.

### 1.1.2 Single-Home Systems (Onsite Septic Systems)

In areas without running water, sewage was often managed by separating it from population centers. For instance, the first sanitation law in Virginia (Virginia Department of Health, 1610), read, in part:

> *"…nor shall anyone aforesaid, within a quarter of one mile from the Pallizadoes, dare to doe the necessities of nature, since by these unmanly, slothful, and loathsome immodesties, the whole fort may bee choked and poisoned with ill aires, and so corrupt (as in all reason cannot but much infect the same) and this shall they take notice of and avoide, upon paine of whipping and further punishment, as shall thought meete, by the censure of a martiall court…"*

As flush toilets gained in popularity, the volume of sewage requiring disposal dramatically increased. During this time the relationship between sanitation and disease also became more widely accepted, and there was a push towards a more hygienic means of sewage disposal: keep it underground. Underground disposal of sewage evolved into leach fields, a practice in which septic tank effluent is dispersed over a large area of land. Since leach pits quickly clog with raw sewage, a settling device (septic tank) was developed (Figure 1-1).

**Hercules Septic Tank for Sewage Disposal**

Instructions furnished with each tank.

*Hercules Septic Tank Where First Stage of Purification Takes Place*

The filter or absorption bed where liquid effluent from tank passes through the final purifying stage before soaking into the soil.

*It Kills the Germs*

Typhoid and other disease germs, in almost every instance, can be traced to contamination of the well by house sewage. A safe and efficient system of sewage disposal is recognized as a necessity for the protection of human life. Hercules Septic Tank is adapted for sewage disposal from any building where running water is available. The natural process of bacterial action provides a safe, effectual and inexpensive means of sewage disposal, as well as an effective protection for your water supply. Hercules tanks are built from high quality Copper Bearing Steel Plate, unexcelled for rust resistance. In addition to this, they are coated with a special rust resisting preservative, making them very durable.

| Catalog No. | Diameter, Inches | Height, Inches | Total Cap., Gals. | Shipping Weight | Capacity Home Use, Number Persons | |
|---|---|---|---|---|---|---|
| 42K3562⅓ | 30½ | 48 | 153 | 165 | 4 | $20.65 |
| 42K3563⅓ | 36 | 48 | 212 | 205 | 6 | 22.40 |
| 42K3564⅓ | 45 | 48 | 331 | 300 | 8 | 28.00 |

**Above prices do not include drain tile.**

***Shipped from factory in WESTERN NEW YORK or NORTHERN ILLINOIS whichever is nearer you.***

Figure 1-1. 1927 Sears Roebuck Advertisement for a Septic Tank.
Reprinted with permission from Alan Mirken (editor), 1970, Crown Publishers Inc. Library of Congress card no. 78-108061.

The septic tank was developed in France in the 1860s (Kriessl, 2002), and a two-compartment septic tank was patented in the United States in 1881 by Edward Philbrick (United States Public Health Service, 1949). Once established in the United States, the septic tank and size of the soil absorption system were codified through prescriptive design standards at the local level. In many jurisdictions, prescriptive septic codes are still used as a de-facto land management tool in lieu of zoning.

Direct application of sewage to a soil adsorption system results in the accumulation of biomass in the pore space of the soil, and is commonly referred to as a biomat. The biomat reduces the ability of the soil to accept wastewater (U.S. EPA, 1980). As organic matter is continually applied, the soil particles eventually clog, leading to hydraulic failure of the adsorption system (Tyler and Converse, 1994). Figure 1-2 illustrates the effect of waste strength on subsurface infiltration rate. Waste streams with high loadings of organic matter, such as commercial and domestic wastes, will exhaust a soil absorption system much faster than lightly loaded waste streams, such as those receiving graywater. Tap water, which contains virtually no organic matter, can be applied to a soil absorption system ad infinitum. Well-managed onsite systems can last 20 years or more, although the average lifespan is much shorter (7–10 years) due to lack of proper operation and maintenance.

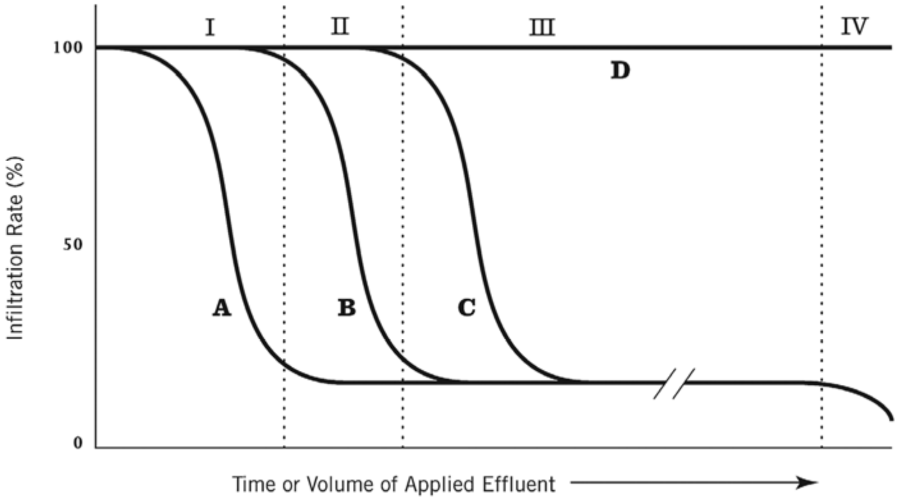


Figure 1-2. Infiltration Rate for Restaurant Effluent (A), Septic Tank Effluent (B), Graywater (C), and Tap Water (D). Reprinted with permission from Tyler and Converse, 1994, American Society of Agricultural Engineers.

In the United States during the early 1900s, adequate backup areas could easily be identified for soil adsorption systems in rural areas of low population density. The growth of the suburbs after World War II began to challenge the assumption that there would always be ample space available for back-up soil adsorption systems; land availability soon became limited. Continuing to use an onsite treatment system coupled with a soil adsorption system was considered an acceptable practice as long as they were perceived as a temporary measure (e.g., until the regional sewer network arrived).

With the recognition that even wealthy countries such as the United States cannot afford to replace all onsite systems with regional sewer networks, there is renewed interest in pretreatment technologies that can extend the effective life of onsite treatment systems by reducing biomat formation and subsequent failure of soil adsorption systems.

### 1.1.3 Cluster Systems

Cluster systems serve a small group of residences. While there are no absolute limits on what constitutes a cluster system, these systems typically serve communities ranging from two to 200 homes. Cluster systems differ from regional sewer networks in that cluster infrastructure provides a collection, treatment, and disposal system for each population node, whereas the regional sewer network attempts to tie all population nodes to a single large treatment works. Cluster systems borrow technology from both the onsite and regional sewer industries. Due to their small size, alternative collection systems such as pressure sewer or small diameter gravity sewer are often used in conjunction with septic tanks (U.S. EPA, 1991). These systems are also more likely to use subsurface dispersal (similar to that of an onsite system) rather than surface water discharge, which is utilized by regional treatment works.

The increasing interest in cluster systems closely tracks the increasing interest in decentralized wastewater management. Cluster systems avoid the high collection costs of regional sewer networks and result in far fewer treatment systems than the single-home approach. Having fewer systems simplifies operation and maintenance, while having multiple users for each system creates the financial wherewithal to adequately fund operation and maintenance.

In developed countries, cluster systems can provide cost-effective sewage treatment for small villages and towns. In the United Kingdom, Severn Trent Water was faced with the need to upgrade treatment works in the early 1990s. Severn Trent had over 1,000 sewage treatment works, 732 of which served populations of less than 2,000. These small works, while representing over 70% of the systems, served less than 3% of Severn Trent's customer base (Green and Upton, 1994). Cluster systems could be a cost-effective solution in Austria, where an estimated 15% of the population (1.2 million people) are living in communities of less than 500 people and still lack wastewater treatment (Haberl et al., 1998). Cluster systems are also becoming popular in new residential developments in the United States.

### 1.1.4 Wastewater Management in Developing Countries

The "Big Pipe" wastewater infrastructure of developed countries does not necessarily provide a road map for cost-effective infrastructure elsewhere in the world. Even in North America and Western Europe, sewage treatment needs still are not being effectively addressed for small communities.

The world population has increased from approximately 2.5 billion people in 1950 to 6.3 billion people in 2003 (United Nations, 2003). Approximately 81% of the world population lives in developing countries (Population Reference Bureau, 2002). As the world population has grown, it has shifted from rural to urban areas. The world's urban population was 2.3 billion in 1990 and is projected to be 4.6 billion in 2020, with 93% of this growth occurring in less developed countries (Mara, 1996b).

The shift from rural to urban areas has created dense population centers that lack basic sanitation facilities. The number of people without adequate sanitation is estimated to be 2.4 billion (Postel, 2003); approximately 38% of the world population. Dense population centers without basic sanitation create conditions ripe for disease. Lack of clean water or sanitation kills an estimated 3.3 million people each year, most of which are children (Postel, 2003). Approximately 40% of the world's population (in over 80 countries and regions) are experiencing water stress (Glieck, 1993), forcing exploitation of water reserves. This short-term strategy is likely to have detrimental long-term effects on the availability of fresh water for human communities and native ecosystems (Kivaisi, 2001). A theoretical framework for sustainable wastewater management has been developed for Zimbabwe (Nhapi et al., 2003), but is applicable to many other regions throughout the globe (see Figure 1-3).

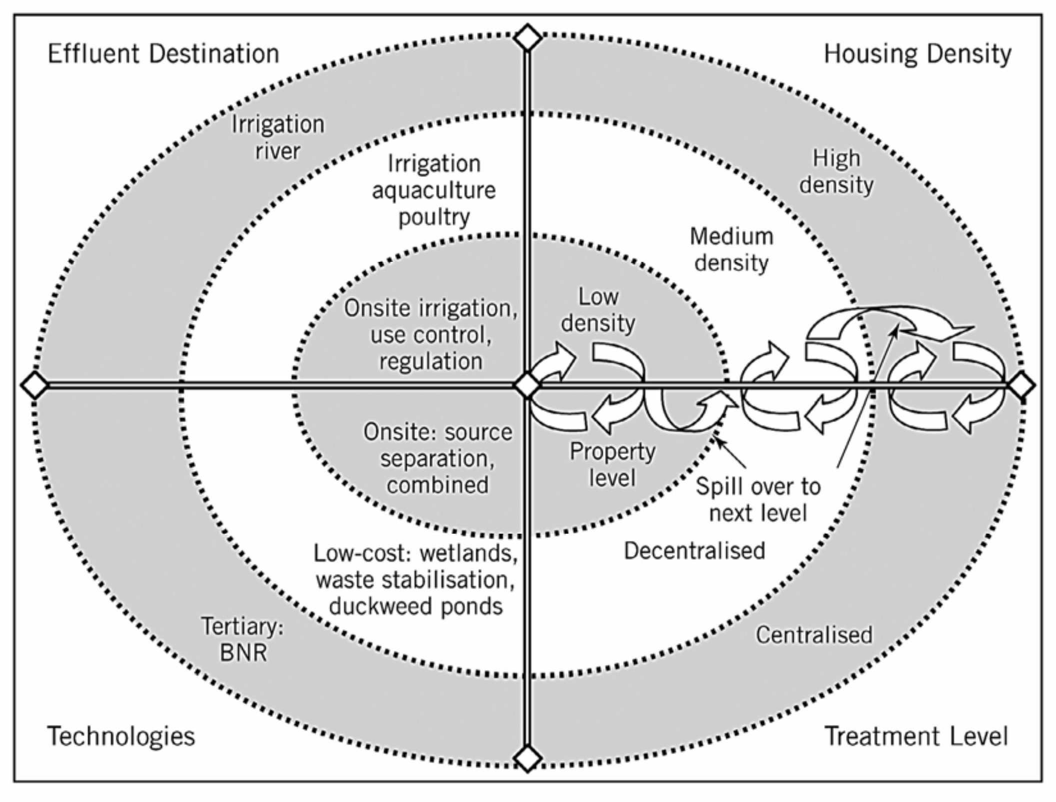


Figure 1-3. Theoretical Approach to Decentralized Wastewater Management.
Reprinted with permission from Nhapi et al., 2003, IWA Publishing.

This model illustrates that for low-density areas, wastewater is best managed at the individual property level, using single-home (onsite) systems with household recycling of effluent water. As housing density increases, the optimum sewage infrastructure cascades into a cluster system approach. At this medium density level, preferred technologies are land-based (simple and low cost) since residents cannot afford full-time operators. Reuse of the effluent for irrigation or other uses is preferred. As housing density approaches urban levels, insufficient space is available for land-based treatment systems and the preferred sewage infrastructure cascades again, this time to a regional sewer network with full-time treatment plant operators.

### 1.1.5 Role of Constructed Wetlands in Decentralized Wastewater Management

Wetland treatment systems use a simple technology that fits very well into both the single-home (onsite) management and medium-density cluster system approach. Specific situations that are good candidates for wetland treatment include:

- Small rural communities where waste stabilization ponds cannot be employed.
- Residential clusters in areas where regional infrastructure is not available or cannot be provided cost-effectively.

- Small businesses, resorts, campgrounds, schools and restaurants that cannot be served by regional infrastructure.
- Individual homes in areas where conventional onsite septic systems have high failure rates, cannot be replaced (due to inadequate backup area), or are not appropriate (due to high groundwater levels).

Constructed wetlands are attached-growth biological filters that distinguish themselves from more conventional treatment processes because they utilize vegetation that is adapted to grow in saturated (or nearly saturated) environments. With the inclusion of vegetation, treatment wetlands have the appearance of a natural wetland habitat and employ many of the biological processes found in natural wetland ecosystems.

Currently there are estimated to be over 50,000 wetland treatment systems worldwide (Kadlec, 2004), with interest in wetland treatment spreading rapidly. Using plants to purify wastewater has tremendous appeal to the general public. Within the regulatory and design community, interest has been sustained because of the simplicity of treatment wetlands. Wetland systems are one of the few technologies that can produce a biologically treated effluent (to secondary or better standards) with a sufficiently low pathogen content. Wetland systems can achieve this level of treatment with minimal external mechanical or energy input and operator support. Because these systems can be constructed from local materials and are simple to operate and maintain, they have the potential for widespread applications in developing countries. Constructed wetlands are currently in use in a variety of countries, including Tanzania, South Africa, Peru, Colombia, Mexico, Egypt, Turkey, Nepal, Thailand, India, and China.

## 1.2 Historical Use of Wetlands for Sewage Treatment

The sewage farming experiences of the 1870s in the United Kingdom led to an appreciation of the link between wastewater application rates, wetland hydrology, plant adaptation, and wastewater purification. It was noted in 1877 that the application of 6 $m^3/m^2 \cdot day$ (147 $gal/ft^2 \cdot day$) of sewage quickly produced a foul-smelling swamp with a polluted effluent; reduction of wastewater applications to 0.05 $m^3/m^2$ (1.2 $gal/ft^2 \cdot day$) with underdrains allowed the sewage farms to operate without soil clogging (Cooper and Boon, 1987). This lead to a standardization of wastewater loadings at about 0.25 $m^2$ per person per day (2.7 $ft^2$ per person per day) (Hiley, 1994), which was sufficient to maintain wastewater application areas as grass plots.

By 1900, the idea of creating wetlands specifically for wastewater treatment had been developed. An essay to the Hornsby Literary Institute, NSW, Australia in 1904 states in part (Brix, 1994b):

> *"…The drainage of suburban houses is always giving trouble and is a matter about which people seem utterly helpless. In districts where there is no sewerage system, householders find that every day they have a large amount of dirty water to dispose of, and the difficulty is to know how to get rid of it. People who live on high ground throw it into an open drain and let it run away to the lower ground where it generates foul gases which breed disease. Others allow all their dirty water to run into the street where it flows along the gutters filling the air with foul odors and causing typhoid and kindred maladies…*

> *If every householder disposed of his own drainage on his own premises as he might very well do, the health of all of us would be much improved. Anyone who has a little ground about his house can dispose of his dirty water as follows:*
>
> *Dig up a plot of ground thoroughly to a depth of fifteen to eighteen inches. Cut a channel leading from the kitchen and washhouse into the highest side of the plot and let all the dirty water drain into it. Plant the plot with plants that grow rapidly and require a great deal of water such as Arum Lilies, for instance. The dirty water will be all absorbed by the roots of the plants and a most luxuriant garden will be produced which will defy the hottest weather and will always be green and beautiful. By this means a curse will be transformed into a blessing."*

The first documented use of a wetland within a deliberately engineered treatment vessel appears to belong to Cleophas Monjeau (Monjeau, 1901), as shown in Figure 1-4.

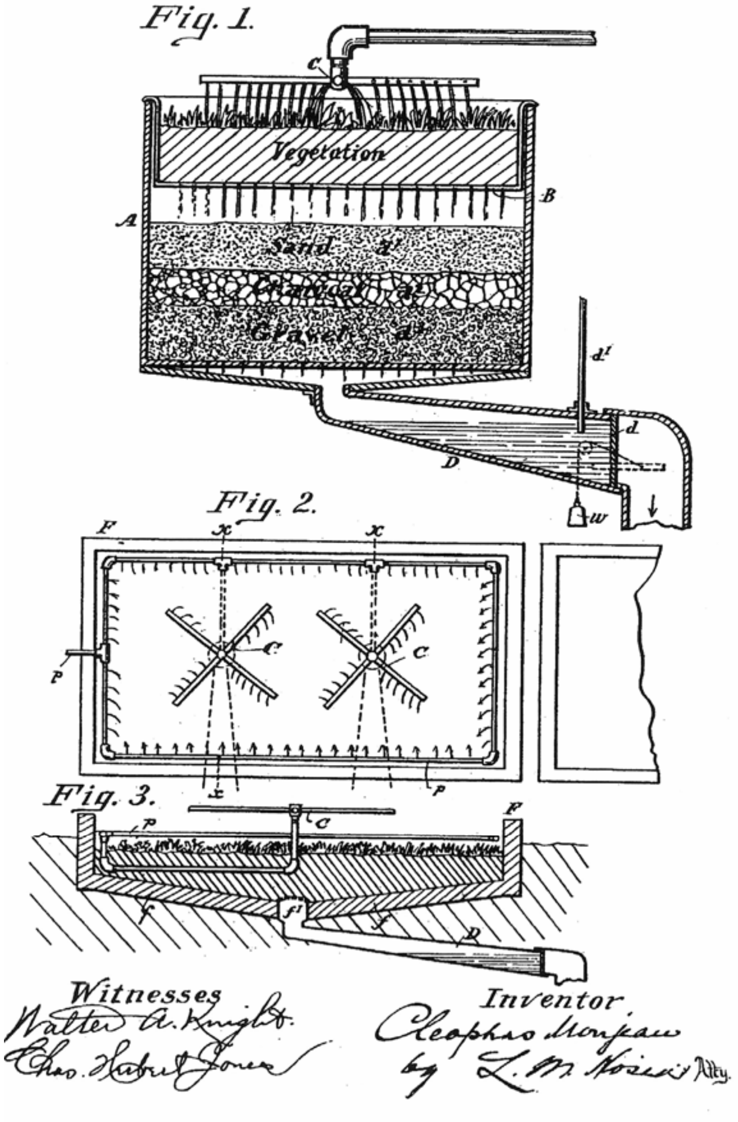


Figure 1-4. 1901 U.S. Patent for a Constructed Wetland System.

Claims for this U.S. patent (issued in 1901) include distributed vertical flow, a fluctuating water level, and aeration of the wastewater. This would be considered a cutting-edge wetland design even in the 21st century.

## 1.3 Types of Constructed Wetlands

Little knowledge from the initial wetland technology of the late 19th century was carried over to the engineered wetlands developed in the late 20th century. Modern constructed wetlands are man-made systems that have been designed to emphasize specific characteristics of the wetland habitat for improved treatment capacity. Treatment wetlands can be constructed in a variety of hydrologic types. The overall technology envelope for constructed wetland systems is summarized in Figure 1-5.

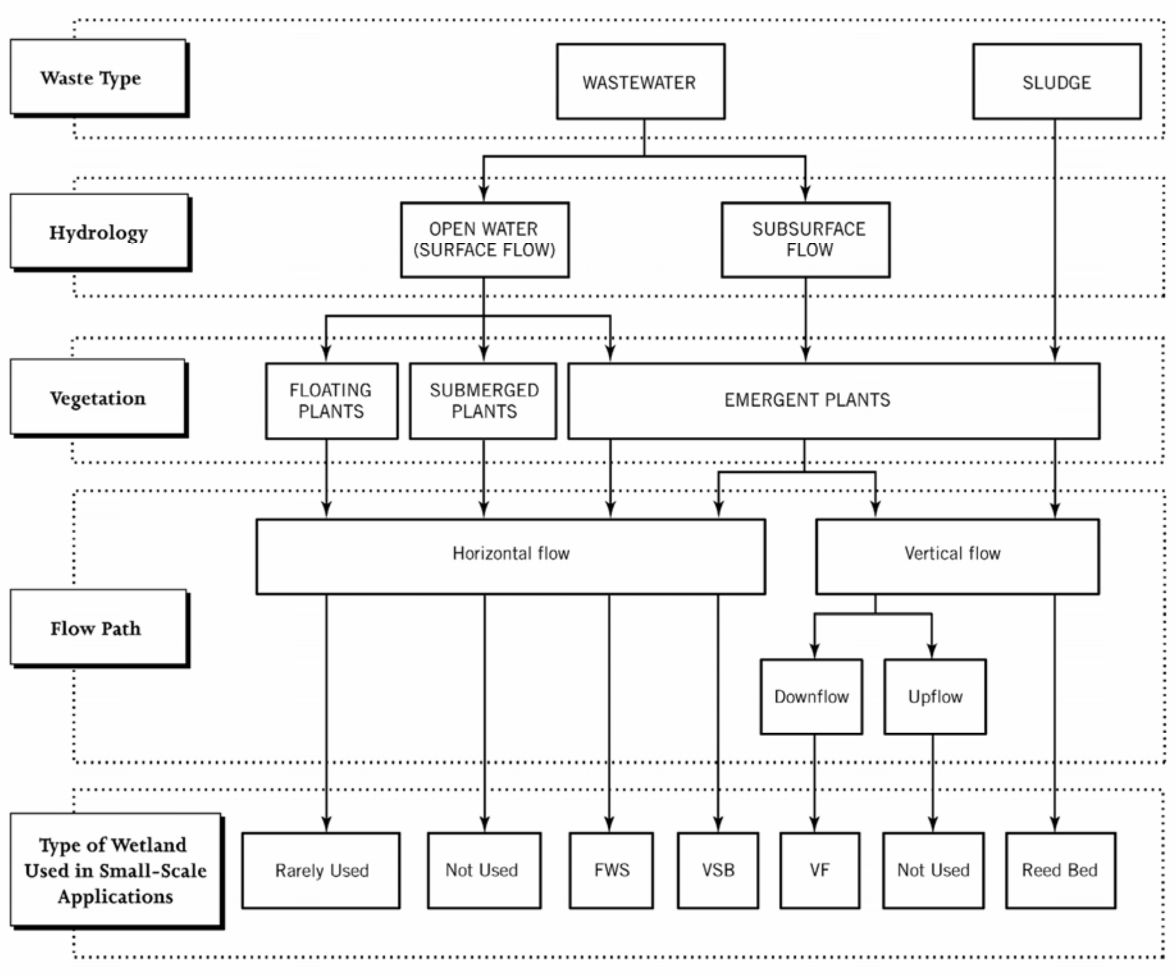


Figure 1-5. Constructed Wetland Technology Envelope.

Four types of constructed wetlands have been found in widespread use for small-scale wastewater treatment applications:

- Free water surface (FWS) wetlands have areas of open water and are similar in appearance to natural marshes.
- Vegetated submerged bed (VSB) wetlands employ a soil or gravel bed planted with wetland vegetation. The water, kept below the surface of the gravel, flows horizontally from the inlet to the outlet.
- Vertical flow (VF) wetlands distribute water across the surface of a sand or gravel bed planted with wetland vegetation. The water is treated as it percolates down and through the plant root zone.
- Sludge dewatering beds (reed beds) use the evapotranspiration capacity of emergent wetland plants (typically *Phragmites*) to dewater sewage sludge.

### 1.3.1 Free Water Surface (FWS) Wetlands

These wetlands contain areas of open water, floating vegetation, and emergent plants. Depending upon local regulations and soil conditions, berms, dikes, and liners can be used to control flow and infiltration. As the wastewater flows through the wetland, it is treated by the processes of sedimentation, filtration, oxidation, reduction, adsorption, and precipitation (U.S. EPA, 2000a). The components in a typical FWS wetland are shown in Figure 1-6.

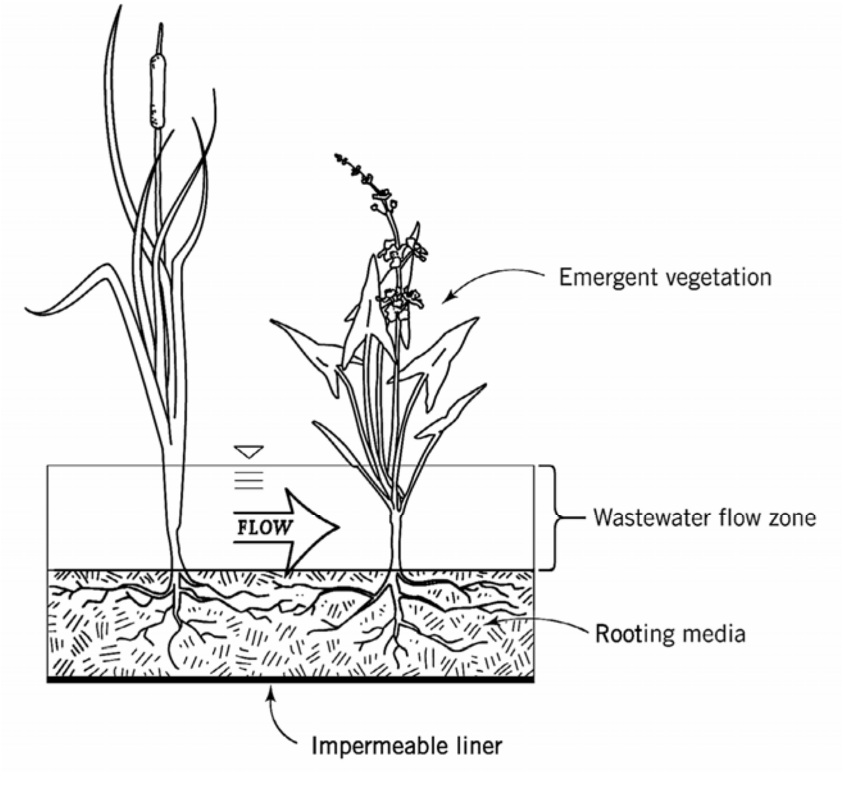


Figure 1-6. FWS Wetland Schematic.

Since FWS-constructed wetlands closely resemble natural wetlands, it should be no surprise that they attract a wide variety of wildlife, namely insects, mollusks, fish, amphibians, reptiles, birds, and mammals (Knight et al., 1993; Kadlec and Knight, 1996). Because of the