Constructed Wetlands: A promising wastewater treatment system for small localities

Experiences from Latin America

water and sanitation program

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Contents

Abbreviations and acronyms

ADA	Austrian Development Agency
ALR	Areal loading rate
BOD	Biochemical oxygen demand
BOKU	Universität für Bodenkultur (University of Natural Resources and Applied Life Sciences), Vienna, Austria
COD	Chemical oxygen demand
CW	Constructed wetland
EPAGRI	Empresa de Pesquisa Agropecuária e Extensão Rural, Brazil
FWS CW	Free water surface constructed wetland
HDPE	High-density polyethylene
HLR	Hydraulic loading rate
IWA	International Water Association
LAC	Latin America and the Caribbean
MPN	Most probable number
NGO	Nongovernmental organization
OLR	Organic loading rate
O&M	Operation and maintenance
PAHO	Pan American Health Organization
PE	Person equivalent
SAAE	Serviço Autônomo de Água e Esgoto de Alagoinhas, Brazil
SDC	Swiss Agency for Development and Cooperation
SEDAPAL	Servicios de Agua Potable y Alcantarillado de Lima, Peru
SF CW	Surface flow constructed wetland
SSHF CW	Subsurface horizontal flow constructed wetland
TSS	Total suspended solids
UNI	Universidad Nacional de Ingeniería (National Engineering University), Managua, Nicaragua
UTP	Universidad Técnica de Pereira (Technical University of Pereira), Pereira, Colombia
VF CW	Vertical flow constructed wetland
WB	World Bank
WHO	World Health Organization
WSP	Water and Sanitation Program, World Bank

Foreword

In Latin America, only 13.7 percent of the collected wastewater receives treatment before it is discharged to the environment or reused in agriculture (WHO and PAHO 2001). Efforts to mitigate negative environmental impacts and reduce public health risks require the development of low-cost wastewater treatment technologies that effectively eliminate wastewater contaminants and are simple to operate and maintain.

This report provides an overview of how constructed wetlands serve as natural wastewater treatment systems. It focuses especially on the subsurface horizontal flow type—a technology that has high potential for small and medium-size communities because of its simplicity, performance reliability, and low operation and maintenance requirements. The ability of this wetland to reduce pathogens renders the effluent suitable for irrigation of certain crop species if additional health and environmental protection measures are taken. This report describes several experiences with constructed wetland schemes in Central and South America: a full-scale pilot plant in Nicaragua, a community-managed constructed wetland scheme in El Salvador, and other systems in Colombia, Brazil, and Peru.

Although the report focuses on technology issues, it stresses the importance of adequate arrangements for operation and maintance to guarantee the long-term treatment performance of the constructed wetland scheme. Furthermore, community participation and complementary actions such as promoting hygiene are crucial elements for sustainable wastewater treatment projects and maximization of health and environmental benefits.

As part of its knowledge management agenda, the Water and Sanitation Program (WSP) promotes the dissemination of this technology. This report is directed at sector professionals, central and local governments, research centers, and donors interested in adopting, promoting, implementing, and financing constructed wetland technology for wastewater treatment, with a view toward improving the well-being of the beneficiary population and the environment.

I would like to express my appreciation to Martin Gauss for preparing this document. An Austrian sanitation expert with WSP-LAC, he has been working in Central America in the field of alternative sanitation technologies, including constructed wetlands, for three years. I also wish to acknowledge the inputs of Hans Brix of Aarhus University in Denmark, Günter Langergraber of the University of Natural Resources and Applied Life Sciences (BOKU) in Austria, and Martin Strauss (retired), formerly with the Department of Water and Sanitation in Developing Countries (SANDEC), Swiss Federal Institute of Aquatic Sciences and Technology (EAWAG).

François Brikké
Regional Team Leader, WSP-LAC

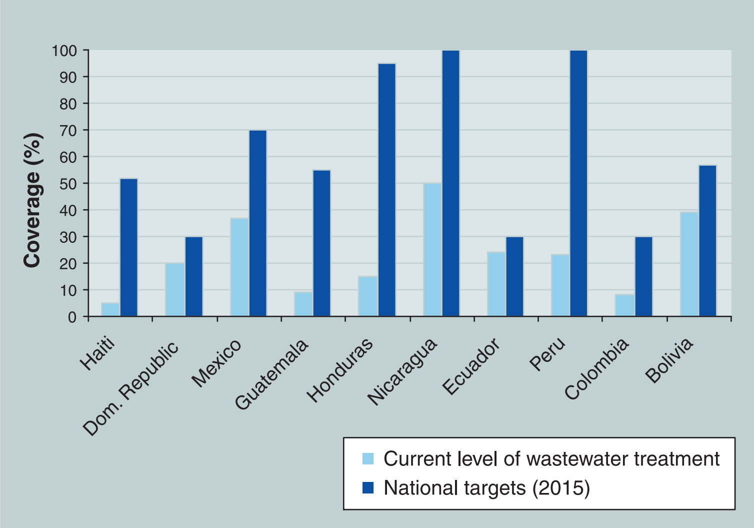
I. Wastewater management

The urban population of Latin America and the Caribbean is growing quickly, and it is expected to rise from the current 77 percent to 80 percent by the year 2015 (UNDP 2006). At the same time, Latin Americans are very demanding of the service level of the water and sanitation infrastructure. In many countries, sewerage systems are the preferred solution to conveying wastewater out of urban areas. However, only a small percentage of the recollected wastewater in the region receives any treatment (figure 1.1).

Untreated wastewater in a poor neighborhood of Iquitos in the Peruvian Amazon. Source: WSP (2007).

The fact that only a small percentage of wastewater is being treated has negative impacts on the region's ecosystems and leads to environmental degradation. Moreover, the reuse of crude wastewater for crop production in many periurban areas of towns and cities could pose severe health risks for farmers, their families, and consumers of contaminated crops. It is estimated that in the region over 500,000 hectares are irrigated with wastewater, most of which has received no treatment (Peasey et al. 2000).

Figure 1.1 Current Level of Wastewater Treatment versus National Targets, Selected Countries in Latin America and the Caribbean



Source: WSP et al. (2007).
Note: Colombia's national target refers to 2010.

Wastewater treatment can be an effective way to protect the environment and public health, especially when wastewater is reused for crop production. Treatment systems based on natural degradation processes, such as stabilization ponds and constructed wetlands, are particularly suited for domestic wastewater treatment where sufficient land is available, because they require little or no energy, are relatively simple to operate, and show reliable treatment performance.

A promising treatment system: Constructed wetlands

Constructed wetlands are natural wastewater treatment systems. Designed to maximize the removal of wastewater contaminants, they consist of beds of aquatic macrophytes (wetland plants). These wetlands are used as secondary or tertiary treatment units—that is, wastewater is generally treated first in primary treatment units such as settling tanks or technical treatment plants. A variety of treatment processes then takes place in constructed wetlands, such as filtration, sedimentation, and biological degradation, which together effectively remove the contaminants in domestic wastewater. In general, constructed wetlands require little operation and maintenance when compared with technical treatment systems.

Flow conditions distinguish the three types of constructed wetland:

1. Surface flow or free water surface constructed wetland (figure 1.2)
2. Subsurface horizontal flow constructed wetland (figure 1.3)
3. Vertical flow constructed wetland (figure 1.4)

These types also differ from one another in system layout, the removal efficiency of certain pollutants, area requirements, technical complexity, applications, and costs. Each type is briefly in the sections that follow.

Surface flow constructed wetland (SF CW) or free water surface constructed wetland (FWS CW)

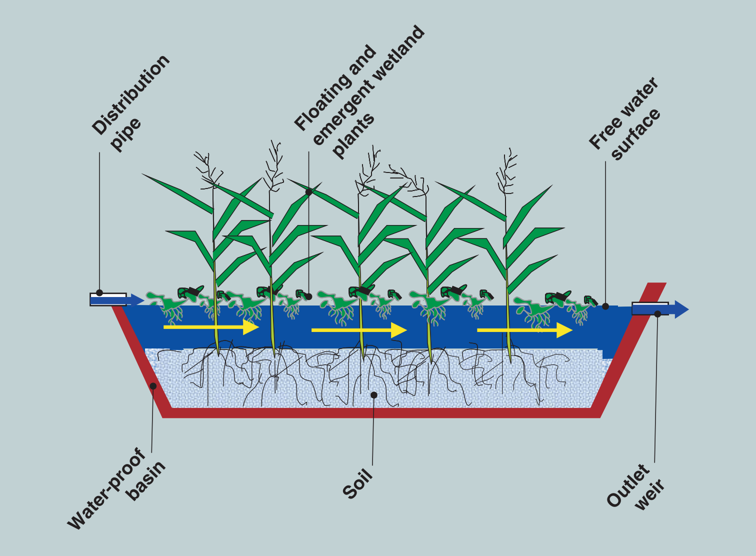
The surface flow or free water surface wetland technology is strongly related to natural wetlands. Wetlands have been used for wastewater discharge for as long as sewage has been collected. After monitoring of some of the discharges began, an awareness of the potential of water quality purification started to emerge. The “technology” arose in the 1970s in North America with the ecological engineering of natural wetlands for wastewater treatment (Kadlec and Knight 1996).

This type of constructed wetland consists of large, shallow lagoons that contain submerged, emergent, or floating plant species. The microorganisms responsible for biological treatment of the wastewater form biofilms on the stems and leaves of the plants. These systems can be used for secondary treatment of wastewater, but they are most commonly used as tertiary treatment—that is, to remove nutrients to prevent eutrophication (algae growth) in the receiving water body.

Subsurface horizontal flow constructed wetland (SSHF CW)

This technology was first investigated in Germany in the 1960s, but it was only about 25 years ago that constructed wetland systems were applied to the decentralized wastewater treatment of single houses, institutions, and small to medium-size settlements. In the meantime, many industrialized countries developed their own national design standards.

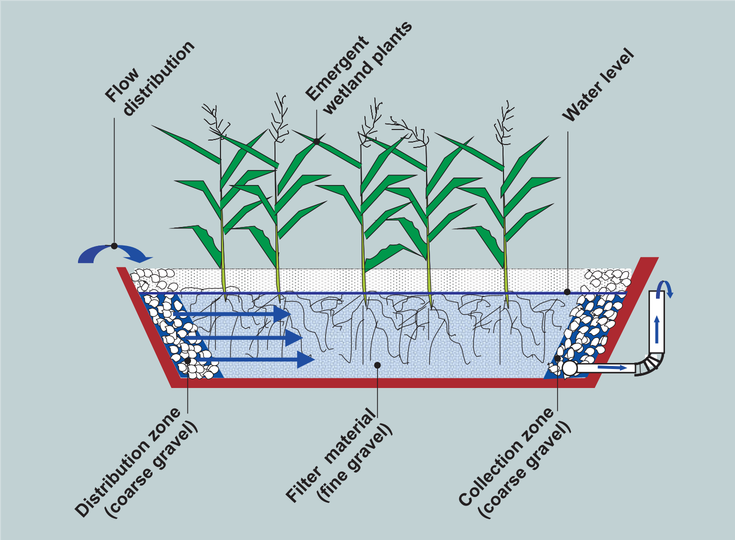
Figure 1.2 Surface Flow Constructed Wetland



Source: Elaboration by the author.

This type of constructed wetland essentially consists of shallow basins filled with coarse sand or gravel as filter material. Locally available wetland plants are grown on the surface of the filter bed, and pretreated wastewater flows through the bed horizontally below the surface. This type of system is described in detail in the following pages. Indeed, the experience gained in Central America and the case studies from South America described in chapter 3 of this document refer *only* to this type. The intensive monitoring and research carried out in Nicaragua have revealed the great potential of these treatment systems and the reuse of their nutrient-rich effluent for irrigation.

Figure 1.3 Subsurface Horizontal Flow Constructed Wetland

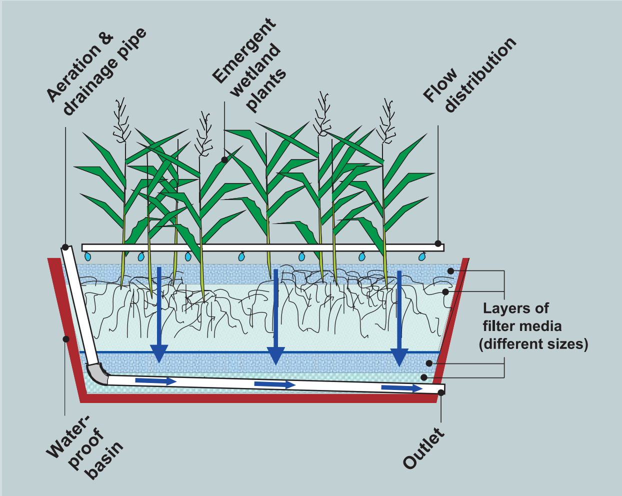


Source: Elaboration by the author.

Vertical flow constructed wetland (VF CW)

The vertical flow type of constructed wetland, developed as an alternative to the SSHF constructed wetland, consists of shallow sand filter beds. A distribution system on the surface of the constructed wetland allows the wastewater to percolate vertically through the unsaturated filter bed. Plants support the vertical drainage process. An important feature of this type is the intermittent hydraulic loading with resting intervals between the single discharges to the vertical bed. This intermittent loading provides an effective aeration mechanism because pores of the filter bed refill with oxygen during the intervals. As a result, high nitrification rates[1] can be achieved in the filters. Denitrification can be carried out by recirculating the effluent into the primary treatment unit (septic tank) to eliminate nitrogen. Because in many European countries discharge regulations related to residual ammonia nitrogen (NH_4) levels have become more stringent over recent years, thereby making nitrification necessary, research in Europe has been focusing on these systems. Vertical flow constructed wetlands are also used for sludge dewatering and stabilization ("sludge humification"). Processes occurring in sludge humification beds differ widely from constructed wetlands for wastewater treatment.

Figure 1.4 Vertical Flow Constructed Wetland



[1] Nitrification is the biological transformation of ammonia nitrogen (NH_4^+-N) to nitrate nitrogen (NO_3^--N) by nitrifying bacteria under aerobic conditions with nitrite nitrogen (NO_2^- -N) as an intermediate product. In a second step ("denitrification"), nitrogen can be removed by conversion of nitrate to nitrogen gas (N_2), which escapes to the atmosphere.

Comparative advantages and limitations

Constructed wetlands are natural treatment systems that offer a variety of advantages that make them suitable for small to medium-size communities in developing countries, particularly in tropical regions. Comparative *advantages,* in particular of the subsurface horizontal flow type, include the following:

- Operation and maintenance (O&M) costs are low because (1) the natural biological treatment processes are enhanced by high ambient and wastewater temperatures; (2) there are low or no external energy requirements; and (3) there is no need for sophisticated equipment, spare parts, and chemicals.
- The O&M requirements are relatively simple, which may allow a community organization or a private, small-scale entrepreneur to manage the system after adequate capacity building and with technical support.
- Constructed wetlands are characterized by robustness, performance reliability, and resistance to flow fluctuations.
- The subsurface flow conditions limit insect breeding and proliferation of vectors.
- Certain wetland plant species grown on the constructed wetland can be reused as animal fodder (such as elephant grass) or ornamental flowers (such as *Heliconia* species) and can generate income.
- Organic pollutants, suspended solids, and helminth eggs can be removed with great efficiency.
- The reduced levels of pathogens in the effluent and remaining nutrients render the effluent appropriate for crop irrigation, provided that additional health protection measures are taken.
- The SSHF constructed wetland has low odor emissions.[2]

- The treatment plant is attractive because of the use of natural materials and plants.
- Constructed wetlands create a habitat for wildlife.

The *limitations* of the technology, and particularly the subsurface horizontal flow type, include the following:

- The surface requirements are high compared with those of conventional technical treatment technologies.
- A relatively large amount of adequate filter material and sealing material is required.
- The deposition of inert solids and biomass can lead to the clogging of certain parts of the filter material.
- The replacement of clogged material is expensive and, in the case of community-managed systems, may not be carried out easily without technical assistance.
- Because of the limited control capacities of local authorities, it is essential that schemes be designed according to the rules of the art and that construction of the systems be carried out carefully and under close professional supervision.

[2] However, the pretreatment and primary treatment units do produce odor emissions.

2. The subsurface horizontal flow constructed wetland (SSHF CW)

Main components

A subsurface horizontal flow constructed wetland is made up of the following principal elements (figure 2.1):

- a waterproof basin
- filter material
- wetland plants
- inlet and outlet structures

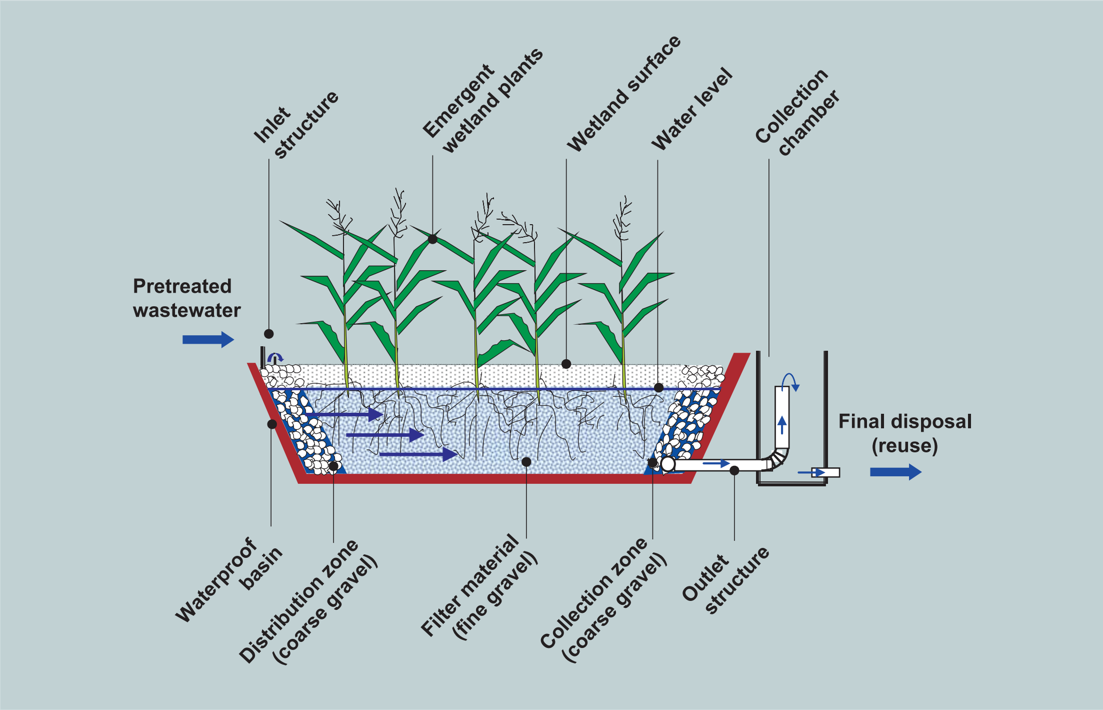
Waterproof basin

A waterproof basin is needed for the constructed wetland in order to avoid soil and groundwater contamination through wastewater infiltration and to prevent infiltration of groundwater into the wetland bed in the case of high groundwater tables. A layer of compacted clay[1] can be installed for this purpose. Alternatively, plastic liners[2] can be used.

Filter material

The filter material fulfills a variety of essential functions in the constructed wetland system and treatment process (see figure 2.2). First, it retains solids from the pretreated wastewater, of which the organic fraction is then further degraded. Second, the filter media provide surface for the adhesion and development of the microorganisms that play a crucial role in the degradation of organic pollutants and transformation of nitrogen compounds. And, third, wetland plants

Figure 2.1 Schematic Cross-section of a Subsurface Horizontal Flow Constructed Wetland

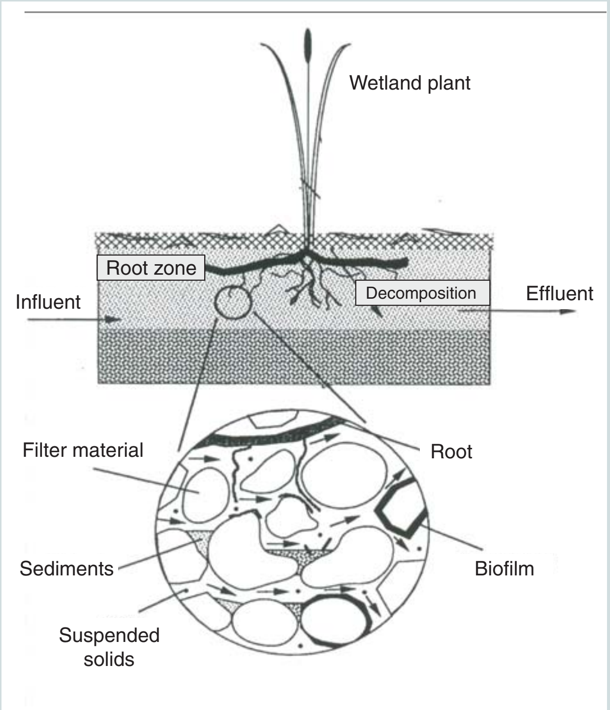


Source: Modified from Platzer et al. (2002).

develop their root systems in the filter material. The water level of the constructed wetland is always kept a few centimeters below the surface of the filter bed by adjusting the standpipe in the effluent collection chamber.

Coarse sand and gravel are preferred filter materials for this type of constructed wetland. Criteria for selecting the filter media are size and granulometry, which determine hydraulic permeability and porosity, and physical resistance to the wear caused by wastewater. Careful selection of the appropriate filter media is of the highest importance for a well-functioning system. Because of its wide availability in Central America, volcanic rock[5] is the most widely used filter material for constructed wetlands in this region (see appendix B for further technical specifications). In the inlet and outlet areas of the SSHF constructed wetland, coarse gravel is used to facilitate wastewater distribution and recollection.

Figure 2.2 Role of the Filter Media



Source: Adapted from Kadlec and Knight (1996).

The volcanic filter material (*hormigón rojo*) used for constructed wetlands in Central America. Source: Martin Gauss, 2006.

[3] At least 30 centimeters thick and with permeability (k_f) of less than 10^{-7} meters per day.
[4] Such as high-density polyethylene (HDPE).
[5] For example, *hormigón rojo* and *hormigón negro*, which are usually available in suitable amounts and granulometry in Central America.

Wetland plants

Wetland plants play several roles in the SSHF constructed wetland. Their root systems provide surfaces for the attachment of microorganisms, enhance filtration effects, and stabilize the bed surface. The roots contribute to the development of microorganisms by the release of oxygen and nutrients. Moreover, the plants give the treatment site an attractive appearance, and some plant species can be used for several purposes after harvesting.

It is recommended that locally available emergent plant species that can tolerate stagnant water conditions be used. In Central America, common reed (*Phragmites australis*) is widely used because of its general availability. Local artisans often then use the reeds to make various products. Other plant species used in the region are elephant grass (*Pennisetum purpureum*), which serves as animal forage, and plants of the genus *Helicona*, which are particularly attractive and colorful.

Different plant species used at the Masaya pilot plant in Nicaragua.
Source: Proyecto Astec, 2005.

Helicona species used as wetland plants.
Source: Proyecto Astec, 2005.

Inlet and outlet structures

Inlet and outlet structures are required for wastewater distribution and collection, respectively. Inlet structures include (buried) distribution pipes or channels, which are installed across the entire width of the wetland's inlet area (see photo). In addition to inlet and outlet structures, it is recommended that coarse gravel be placed in the inlet and outlet areas of the constructed wetland to enhance flow distribution and effluent collection.

The outlet structure for the recollection of the treated wastewater consists of a drainage pipe laid at the bottom of the outlet area. It is connected to an effluent collection chamber. Inside the collection chamber, a flexible standpipe or hose allows adjustment of the water level in the filter bed.

Inlet distribution system at Masaya, Nicaragua.
Source: WSP, 2006.

Removal mechanisms for pollutants and efficiency

A variety of complex biological, physical, and chemical mechanisms improve the water quality in constructed wetlands. These mechanisms are based on the interaction between the wastewater, microorganisms, plants, and filter material. The major mechanisms, which cater to the removal of several constituents from domestic wastewater, are described in table 2.1. The removal efficiency of constructed wetlands essentially depends on the applied *hydraulic surface loading rate*[6] and the filter material. The high ambient and wastewater temperatures prevailing in the region enhance the biological degradation processes.

Table 2.1 **Main Removal Mechanisms in SSHF Constructed Wetlands and Average Removal Efficiencies**

Wastewater constituent	Main removal mechanism	Removal efficiency in constructed wetland bed
Organic matter	*Biological* degradation (by microorganisms)	High (80–90%)
Suspended solids	*Physical* sedimentation, filtration *Biological* degradation	High (80–90%)
Nitrogen	*Biological* ammonification, nitrification–denitrification	Low (approx. 20–40%)
Phosphorus	*Chemical and physical* absorption processes in the filter material	Low (approx. 20%)
Pathogens		
[a]Thermotolerant coliforms	*Biological* predation, natural die-off	Medium (1–3 log units)[c]
[b]Helminth eggs	*Physical* sedimentation, filtration	High (up to 3 log units)[d]

[a] Pathogens such as bacteria, viruses, protozoa, and helminth eggs are disease-causing microorganisms.
[b] Thermotolerant coliforms are commensal bacteria of the human intestine that serve as indicators of fecal pollution. Residual thermotolerant coliform concentrations are indicative of the effectiveness of the treatment process in removing bacteria, viruses, and protozoa.
[c] Because of the large number of pathogens contained in wastewater, removal efficiency is expressed in log units rather than in percentages. A 1 log unit reduction corresponds to 90 percent removal efficiency, 2 log units to 99 percent, 3 log units to 99.9 percent, and so on.
[d] According to WHO (2006).

[6] Amount of wastewater applied per square meter of constructed wetland area and day.

Operator observing effluent quality at Masaya, Nicaragua.
Source: WSP, 2006.

Organic matter

Microorganisms, which provide biological treatment, effectively degrade organic pollutants. Efficiencies are usually higher than 90 percent in terms of biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD).[7]

Suspended solids

Physical settling and filtration effects in the filter material reduce the amount of suspended solids. Subsequently, microbes will degrade the organic solids, whereas inorganic solids accumulate in the empty spaces in the filterbed, where they will cause clogging. The removal efficiencies for total suspended solids (TSS) are usually 80–90 percent.

Nutrients: Nitrogen (N) and phosphorus (P)

In SSHF constructed wetlands, the percentage of nitrogen removed is relatively small (about 30 percent) because of the low oxygen availability in the filter media. The largely oxygen-free conditions in the substrate of the bed limit nitrification, the first step in (biological) nitrogen removal. Some nitrogen is taken up by the plants growing on the wetland, but the amount is usually small compared with the amount of nitrogen loaded into the wetland by the wastewater.

Phosphorus is removed by the chemical adsorption processes of the filter media and to a lesser extent by plant uptake. Removal efficiency depends essentially on the sorption[8] capacity of the filter material, which decreases over time, requiring replacement of the filter media. The average removal efficiency of phosphorus is relatively low. In Central America's constructed wetlands, about 20 percent of total phosphorus is removed using volcanic sand as filter media.

The amount of nutrients removeable by harvesting is insignificant compared with the loadings of wastewater. If the wetland is not harvested, the nutrients incorporated in the plant will be returned to the water during decomposition of the plants (Brix 1997).

The relatively low removal of nutrients might be disadvantageous, because it causes eutrophication[9] in receiving water bodies. However, crops will benefit from the remaining nutrient load when irrigated with the effluent of SSHF constructed wetlands.

Pathogens

Pathogenic microorganisms, retained in the filter media by filtration, sedimentation, and adsorption, are later

7 BOD_5 refers to the five-day biochemical oxygen demand—that is, the amount of dissolved oxygen that disappears from a water sample in five days at 20º C through decomposition of organic matter by microorganisms. COD refers to chemical oxygen demand—that is, a measure of the oxygen equivalent of the organic matter in water based on the reaction of a strong chemical oxidant.

8 Sorption in general refers to phenomena such as chemical binding and physical dissolution, which are responsible for trapping a variety of chemical constituents (Kadlec et al. 2000).

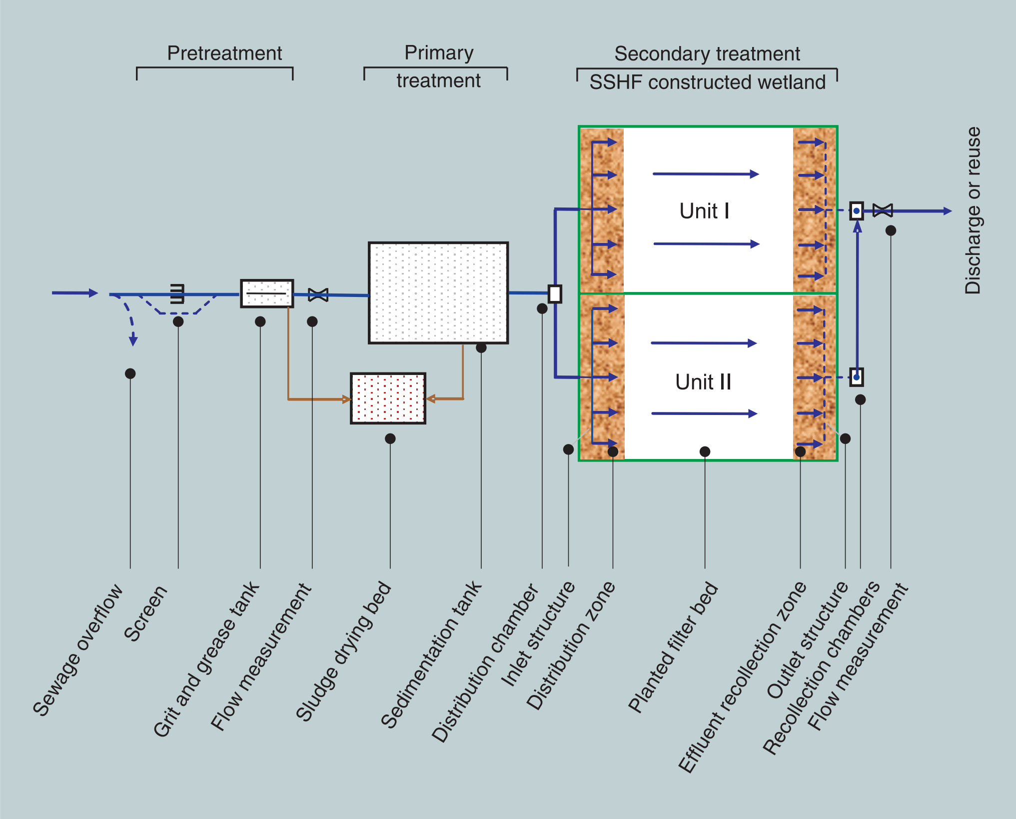
9 Excessive algae growth stemming from a high content of nutrients.

eliminated or deactivated by mechanisms such as predation and natural die-off. Common removal efficiencies for thermotolerant coliforms are in the range of 1–3 log units, depending on the hydraulic retention time of the system, granulometry of the filter media, and temperature. As for the important public health hazard associated with helminth eggs, removal rates of 1–3 log units have been reported (WHO 2006). The risks posed by pathogens are important to consider, particularly when reusing the effluent for crop irrigation. More information on this topic appears later in chapter 2.

Basic layout of SSHF constructed wetland systems

Domestic and municipal wastewater contains large solids and fine suspended matter, as well as dissolved organic and inorganic contaminants and enteric pathogens. To remove these pollutants, a SSHF constructed wetland *system* contains at least the following treatment stages[10] (see figure 2.3).

Figure 2.3 Basic Layout of a SSHF Constructed Wetland System



Source: Elaboration by the author.

[10] The layout concept refers to SSHF constructed wetland schemes as predominantly used in Central America and other countries in the region. However, pretreatment and primary treatment units may vary, and even additional treatment reactors may be implemented before the constructed wetland units as in Colombia or in some cases in Brazil (see the case studies in chapter 3 of this report). In general, stabilization ponds are not recommended as the primary sedimentation unit because of algae, which could clog up the filter media (USEPA 1999).

For the vertical flow constructed wetlands described briefly in chapter 1, the French research institute CEMAGREF has developed a configuration that allows direct application of crude domestic wastewater to a series of constructed wetlands, using the first stage for sludge stabilization of the biosolids. Reference plants have been installed in France and other European countries of Europe (see also Molle et al. [2005] and http://www.lyon.cemagref.fr/qe/epuration/Guide-Macrophytes.pdf for further information).

Pretreatment

The pretreatment stage consists of a manually cleaned screen to hold back bulk objects. In addition, it is recommended that a simple grit and grease removal unit be provided, because people tend to connect their stormwater drain pipes to the sewerage system, which results in large amounts of fine solids in the wastewater during the rainy season. Coarse solid residues from the screen can be burned or deposited at the municipal garbage site. Hydraulic overloading of the system can be prevented by installing an overflow device to divert peak flows during rain events. A simple flow measurement device, such as a Parshall channel (see photo), can be installed after the pretreatment unit to monitor the flow rate.

Flow measurement (Parshall channel) and Imhoff tank at the SSHF constructed wetland scheme at Masatepe, Nicaragua. Source: Martin Gauss, 2005.

Primary treatment

Settleable and suspended solids, as well as organic material adhering to them, are trapped and form sludge at the bottom of the primary sedimentation tank, which can be designed as a septic tank or Imhoff tank.[11] These units also provide partial digestion of the settled sludge. If these tanks are covered, a simple biofilter (a box filled with humidified bark) can be installed to eliminate unpleasant odors. The primary treatment is an important treatment stage ahead of the constructed wetlands, because effective separation of solids prevents the constructed wetland from clogging. Land requirements for the subsequent constructed wetland units essentially depend on the efficiency[12] of this treatment stage.

Sludge treatment

The sludge generated in the first two stages (grit and grease trap, sedimentation tank) is collected and transferred to a sludge treatment unit, such as a sludge drying bed.[13] The sludge remains on the drying beds for several weeks up to a few months to permit its dewatering, stabilization, drying, and hygienization—that is, deactivation of the pathogenic microorganisms. Alternatively, the dewatered sludge may be removed from the beds upon reaching the consistency of sludge

[11] A *septic tank* is a watertight chamber that receives (household) wastewater. The tank, which consists of two or three compartments, serves several purposes: as a sedimentation tank for the removal of incoming solids, while allowing the liquid fraction (or settled effluent) to pass; as a biochemical reactor for the anaerobic decomposition of the retained solids; and as a storage tank in which the nondegradable residual solids accumulate. Scum, such as fats and grease, rises to the top. An *Imhoff tank,* which fulfills the same purposes, consists of a top compartment, which serves as a settling basin, and a lower compartment in which the settled solids are anaerobically stabilized. Scum and gas vent chambers are located at the sides of the tank. The tank can be open or covered. These descriptions were taken from the *Philippines Sanitation Sourcebook and Decision Aid* (WSP et al. 2005).

[12] The efficiency of the primary treatment units in terms of the removal efficiency of suspended solids and BOD_5 depends essentially on the hydraulic retention time in the case of septic and Imhoff tanks. See Crites and Tchobanoglous (1998) and the *Philippines Sanitation Sourcebook and Decision Aid* (WSP et al. 2005) for design recommendations.

[13] Sludge drying beds are a low-cost treatment option for septic sludges. See appendix C for a summary of design principles of sludge drying beds and the Web site of EAWAG SANDEC, http://www.eawag.ch/organisation/abteilungen/sandec/publikationen/publications_ewm/index_EN, for more information.

Sludge evacuation system at the Imhoff tank, Masatepe, Nicaragua.
Source: Martin Gauss, 2005.

Sludge drying bed at Masatepe, Nicaragua. Source: Martin Gauss, 2005.

and therefore spadable and stored in a roof-covered area for drying and hygienization before its use as a soil conditioner.

Secondary treatment

The secondary (or biological) treatment through the constructed wetland. removes organic matter, suspended solids, and microbiological pollutants. The filter bed should contain coarse gravel at the distribution and collection zone and fine gravel for the planted area in between. A constructed wetland scheme should have at least two constructed wetland units to permit independent maintenance.

Implementation requirements

The following considerations should be taken into account when selecting a SSHF constructed wetland as an option for wastewater treatment.

General prerequisites

Reliable and sufficient water supply. A reliable water supply system with sufficient water flow is required to guarantee trouble-free operation of the wastewater collection system. A piped water supply and household connections are therefore the minimum level of services required.

Sewerage system. A constructed wetland system, as an off-site treatment option, depends on an effective wastewater collection (sewerage) system, which requires a certain population density to be cost-effective. Households must connect to the sewerage network from the start of sewerage operations. In this context, the condominial approach[14] could be considered.

[14] Condominal water and sewerage systems, successfully implemented in Brazil, Bolivia, and Peru, offer a variety of advantages over conventional systems, including a significant reduction in investment costs. For further information, please see Melo (2005).

Stormwater management. Combined sewerage networks as well as illegal stormwater connections to a separate sewerage network can lead to hydraulic overloading and high concentrations of solids in the influent of the treatment plant. To protect the treatment system, a hydraulic overflow device must be installed to divert wastewater exceeding the design flow.

Determination of wastewater characteristics, flow rate, and flow variations.
The characteristics of municipal wastewater can differ greatly from those of domestic wastewater in types of contaminants and pollution loads because of the industrial effluents discharged into municipal systems. High concentrations of toxic substances can inhibit the biological treatment process in constructed wetlands. Moreover, wastewater diluted by groundwater infiltration into the sewerage system will reduce treatment efficiencies.

Knowledge of the locally specific or expected wastewater characteristics and of the flow rate and flow variations are fundamental for the successful implementation of wastewater treatment plants.

Requirements of constructed wetland technology

Area requirements. The construction of a constructed wetland system depends on the availability of a large tract of land to accommodate pretreatment devices, primary treatment units, and the constructed wetlands. Area requirements for *primary treatment* depend on the type of unit(s) installed. Appendix B provides estimates for various options.

Land requirements for the constructed wetland units depend on various factors, such as wastewater temperature, the required effluent quality, and the areal loading rates[15] of certain pollutants. According to detailed investigations carried out in Nicaragua, approximately 1.5 square meters of wetland surface area per person[16] are required under the local conditions to achieve appropriate levels of contaminant removal and to limit colmatation of the filter media. However, this is *not* a standard value but rather a rough rule of thumb. Depending on the previously mentioned factors, the area requirements might increase to 3–5 square meters of wetland surface area per person and therefore would have to be estimated on a case-by-case basis.

Additional area is needed for the sludge drying bed[17] and other infrastructure, such as pathways and a storage room for O&M tools.

Availability of construction materials. Reinforced concrete is required for the inlet, pretreatment, and primary treatment units. Sufficient quantities of adequate filter material must be available, because the filter media are one of the most important elements of the system. Clay, which is used to seal the bottom and sidewalls of the constructed wetland, is another important construction material. Alternatively, a high-density polyethylene (HDPE) liner can be used. Distance from the supply site to the construction site substantially influences construction costs.

[15] The areal loading rate (grams per square meter per day) is calculated by multiplying the influent flow rate (cubic meters per day) by the respective influent pollutant concentration (milligrams per liter equal grams per cubic meter), and dividing by the surface area (square meters) of the SSHF constructed wetland (USEPA 1999). Recommended limits, drawn from the experience in Nicaragua and international literature, can also be used to estimate the area requirements of the SSFH constructed wetland (see appendix B).

[16] According to experiences in Nicaragua, each inhabitant generates *on average* about 100 liters of wastewater, and the average concentration of BOD_5 is about 270 milligrams per liter. This concentration generates a BOD_5 pollutant load of about 27 grams per day, which is further reduced by the primary treatment unit to about 9 grams per day (see table 3.1, chapter 3, for the local characteristics of raw and pretreated wastewater in Masaya, Nicaragua). The recommended areal loading rates for BOD_5 and suspended solids (stated in appendix B) justifies the area requirement of 1.5 square meters per person equivalent under the conditions just listed.

[17] Cofie et al. (2006) suggest 0.08 square meters per person.

Adequate construction site. The construction site for the system must be stable and adequately drained to avoid flooding of the entire site, including the treatment units. A topography offering an adequate slope would be desirable to avoid pumping and the related energy requirements. The groundwater level must be sufficiently deep to avoid problems during and after construction. Complete sealing of the constructed wetland beds is compulsory to avoid seepage and groundwater contamination.

Capacity of SSHF constructed wetland systems. In theory, there is no upper limit on the maximum flow rate and the corresponding size of the constructed wetlands, provided that larger systems are subdivided into single units, restricting their width and length[18] to control hydraulic conditions and facilitate O&M (Brix 2007). In practice, however, the maximum flow rates of systems will be determined by factors such as the availability of land and suitable filter media, as well as the associated costs, compared with those of other (technical) treatment options. So far, at the global level the majority of SSHF constructed wetlands have been applied to small to medium-size communities of up to 5,000 people.

Environmental impact

This section provides an overview of the environmental impacts of liquid emissions, solid by-products, and odors arising from SSHF constructed wetland schemes.

Liquid emissions

By decreasing pollutant loads, a well-functioning SSHF constructed wetland system substantially reduces the negative impact of wastewater discharged to the environment. The nutrients that remain in the effluent of the systems can be exploited for crop

irrigation. Raw wastewater *and* the treated effluent, although to a much lesser level, contain enteric pathogens, which can cause diseases such as diarrhea, typhoid, schistosomiasis, ascariasis, hookworm disease, hepatitis, and cholera. Operating personnel must therefore wear the appropriate safety items such as gloves and boots so that they avoid direct contact with wastewater. Personnel also should be made aware of good hygienic practices such as avoiding hand-to-mouth contact during work. Wastewater reuse for irrigation requires the application of additional health protection measures (see the section on effluent reuse in chapter 3).

Solid by-products

Solid residues arising from constructed wetland schemes include coarse screenings, partially digested sludge, clogged filter material, and harvested wetland plants.

[18] See appendix B for recommendations.

Coarse solids trapped in the pretreatment unit can be burned or buried on-site or transported to a waste disposal site. Sludge from grit removal units and primary settling tanks is stored and stabilized in the sludge drying bed. Primary settled sludge can contain considerable concentrations of highly infective pathogens such as helminth eggs, which can persist for several months. These wastes should be handled with caution. After several months of dewatering, stabilization, and drying, the dried sludge can be used as a soil conditioner.[19] Like the treated wastewater, the biosolids could constitute another source of income from the treatment operations.

Clogging usually occurs just behind the inlet distribution zone in the main filter material. The pilot plant in Masaya, Nicaragua, found that parts of the filtering body became clogged after two to two and a half years,[20] leading to surface flow. The clogged material must then be removed by lowering the water level and replaced by new material to reestablish subsurface flow conditions. It can be dried and stored on-site, covering it with soil. Alternatively, it can be taken to a landfill for disposal.[21]

Odor emissions

The subsurface flow conditions keep odor emissions from the constructed wetland to a very low level. Odor emissions do arise, however, from the pretreatment units, where raw wastewater is handled, as well as from the primary and sludge treatment units. In addition, odorous biogas, produced by anaerobic processes in the primary settling tank, can be captured and treated in a low-cost biofilter,[22] as experience at the Masaya pilot plant in Nicaragua showed. Thus, depending on the size of the system and local climatic conditions, the constructed wetland must be situated at an adequate distance from human settlements.

Other impacts

Although insect breeding is avoided because of the subsurface flow in the wetland, the generally humid conditions and the presence of plants do not guarantee a complete absence of mosquitoes and other insects.

Generally, constructed wetlands are aesthetically attractive systems because of the use of natural materials and plants. During the dry season in Central America, they are one of the few green areas. In Lima, located on Peru's arid Pacific coastline, the wetlands are green islands amidst the desert landscape.

Design and construction

An experienced sanitary engineer must carry out the design of a constructed wetland system, including the pretreatment and primary treatment units. Efficient primary treatment to reduce suspended solids, thereby avoid frequent clogging of the filter material, is key to the successful operation of a SSHF constructed wetland. Implementation of the constructed wetland must be based on a thorough technical design, ideally including:

- Knowledge of wastewater flow and wastewater characteristics such as pH, temperature, and content of organic solids, suspended solids, and pathogens

[19] For tropical areas (that is, those with temperatures of 20–35°C), World Health Organization (WHO) guidelines recommend more than four months of storage time to achieve 70–90 percent deactivation of Ascaris eggs and one year of storage time to achieve complete deactivation. WHO's standard for fecal sludge reuse in agriculture is less than one viable helminth egg per gram of total solids (WHO 2006).

[20] This period depends on the granulometry of the filter media used, contaminant loading rates, and other factors.

[21] According to experiences in England, gravel (without fine fractions) can be washed and reused (Brix 2007).

[22] A box containing humidified bark, which acts as a support material for the microorganisms responsible for the biological degradation of odor emissions.

- Knowledge of the treatment efficiency of treatment stages *ahead* of the constructed wetlands
- Relevant characteristics of the filter material (hydraulic permeability and granulometry) to estimate its hydraulic capacity
- If possible, scientific data on degradation constants for the main wastewater pollutants (or rules of thumb) to estimate area requirements and effluent quality. These data could be derived from pilot installations under site-specific conditions.[23]

Design criteria include hydraulic surface load, organic and TSS areal loading rates, and the granulometric characteristics of the filter material, which determine its hydraulic capacity and therefore influence dimensions of the constructed wetland. The reduction in filter permeability over time because of the accumulation of solids and root development should be compensated by applying a safety factor in estimating the design hydraulic permeability of the material (Kadlec and Knight 1996; USEPA 1999).

Construction of wetlands might seem to be rather simple. However, considerable care must be taken to avoid operational problems arising from design or construction errors. Once the constructed wetland is built, it is almost impossible to make changes or adjustments, and there are only limited possibilities for influencing the treatment process of the system. Constructed wetland systems can be installed by drawing on the local labor force and using locally available construction materials under the supervision of an experienced field engineer.

The inlet channel, pretreatment, and primary treatment works are usually made of reinforced concrete. Ferrocement could be used to construct the settling or septic tanks as a low-cost alternative. The materials required for the constructed wetland itself include filter material (fine gravel for main material and coarse gravel for inlet and outlet zones), sealing material (compacted clay or HDPE cover), and pipes for flow distribution and effluent collection systems.
The sidewalls and the bottom of the constructed wetland must be sealed to avoid infiltration losses and groundwater contamination. It is recommended that the wetland be divided into at least two separate units (for example, using concrete plates) to allow independent operation and maintenance of each unit. The filter media should be selected carefully; material that contains very fine fractions has low hydraulic capacity and can lead to frequent clogging and surface flow conditions. The filter media must be placed evenly, avoiding compaction, which could result in short-circuiting. Coarse filter media to evenly distribute and recollect the wastewater are placed at the inlet and outlet zones after installing the outlet drainage pipe. The coarse filter material in the distribution zone also acts as a prefilter, offering sufficient pore volume for the accumulation of solids and biomass. It can be extended (up to 4 meters) in order to limit clogging of the subsequent finer material. The flexible pipe or hose installed in the effluent collection chamber is essential for control of hydraulic conditions, including adjustment of the water level in the constructed wetland, keeping it always below the surface.

Operation and maintenance

One operator, adequately trained, can manage the treatment plant, although additional personnel might be required on a temporary basis. The use of safety items such as gloves and boots is highly recommended to protect the operator from adverse health effects.

[23] Taking into account characteristics of the filter material, climatic conditions, and hydraulic surface loading and organic and TSS loading rates. For further information on the design parameters, recommended areal loading rates, and degradation constants for Central America, see appendix B, as well as Platzer et al. (2002) and Proyecto Astec (2005).

The time required to carry out the various O&M tasks for the entire system is described in the rest of this section, based on experience drawn from O&M of the pilot plant in Masaya, Nicaragua, that serves about a 1,000 people. The capacity of this plant is considered to be representative of a constructed wetland system. However, the time required for O&M tasks for bigger plants may vary slightly. See appendix A for a list of routine O&M activities.

Measuring the flow. Source: WSP, 2006.

Inlet channel and screen

- Remove daily the coarse solids retained by the screen using a metal rake. Bulk material (such as plastics) is collected and transported to the municipal garbage site; organic material is deposited in the sludge drying bed. *(10 minutes per day)*
- Remove monthly the sediments from the bottom of the inlet channel using a shovel and wheelbarrow. *(30 minutes per month)*
- Record the influent flow, observing the installed flow meter (Parshall channel, etc.). Take hourly measurements at first to familiarize the operator with the inlet and outlet flow patterns. Later, measurements can be taken less frequently (three times a day). These measurements should be recorded in the operator's book in order to observe the flow pattern over time. *(5 minutes per measurement)*

Cleaning the inlet channel. Source: WSP, 2006.

Sand and grease trap

- Extract the grit that accumulates at the bottom of the grit trap, using a shovel and a wheelbarrow. Alternatively, extract the grit by means of a drain pipe (including a valve) at the bottom of the unit connected to the sludge drying bed. Cleaning frequency will depend on the concentration of solids in the influent. Often, the stormwater drains connected to the sewerage system account for the high concentrations of solids during the rainy season. *(30–40 minutes per cleaning)*
- The grease that accumulates as scum on the surface of the grit tank is retained by a simple baffle installed at the end of the tank. Remove the scum every three days using a surface skimmer or shovel and wheelbarrow. *(15 minutes per cleaning)*

Sedimentation tank (three-chamber septic tank or Imhoff tank)

- Using a shovel or surface skimmer, remove the scum that forms at the surface of the tank because of the buoyant sludge particles. Use a wheelbarrow to transport the wastes to the sludge drying bed. *(15 minutes every two weeks)*
- Using a surface skimmer, remove the surface scum that forms in the sedimentation chambers and is retained by the deflector walls at the end of these chambers. Use a wheelbarrow to transport the wastes to the sludge drying bed. *(1 hour per month)*
- Generally, sludge from the primary sedimentation tanks contains high levels of pathogens. Take the appropriate caution to avoid contact when handling the sludge. Sludge should be removed according to the sludge storage capacity of the tank defined in the design (generally every six months). Remove the sludge by installing a sludge evacuation pipe and valve connected to the sludge drying bed or by using an adequate pump. A small amount of lime could be spread over the fresh sludge to control odors and enhance dewatering. *(1–2 hours)*
- Dewatered sludge can be removed after two to three weeks—that is, after it has reached spadability. It can then be stored in a roof-covered area for about one year. Alternatively, if a sufficient drying bed area is available, the sludge can be left on the drying beds until it dries completely, which will reduce the required storage time for hygienization. *(3 hours)*
- If a biofilter is used to control odors, the bark inside the filter should be kept humid and replaced once a year. *(5 minutes per week)*

SSHF constructed wetland

- Remove monthly the sedimented particles from the influent distribution channel, and, if needed, replace the wooden covers of the channels. *(30 minutes per month)*
- Harvest the plants according to their growth cycle (for example, every 10 months for reed and every three months for elephant grass in Central America). Afterward, clean the filter bed surface, using adequate cutting devices and a rake. It has been estimated that one person can cut and clean

Removing the surface scum from the sedimentation tank. Source: WSP, 2006.

Operator discharging sludge from the grit tank to the drying bed. Source: WSP, 2006.

Harvesting the wetland plants. Source: Proyecto Astec, 2005.

50 square meters per day. It may then be necessary to hire additional personnel for these activities to assist the plant operator. Local people might be willing to assist free of charge in exchange for the plants, which are used by artisans (reed) or for animal feed (elephant grass).

- When surface flow becomes apparent in certain parts of the main filter media (usually just behind the distribution zone), it is advisable to replace the clogged material. This activity is carried out by diverting the flow to the second unit so that water can be extracted from the first unit by lowering the flexible pipe or hose installed in each collection box. A shovel and wheelbarrow are needed for these activities, and it may be necessary to hire additional personnel to minimize the amount of time the constructed wetland unit is out of operation.

Community participation in the implementation process

Community organization and participation of the community in all stages of the project are key factors in the sustainability of a wastewater treatment system. The participation of the local community is especially important when selecting the preferred technology. This process must be accompanied by information on each technology's O&M and management requirements, as well as the investment and recurrent costs for each technical option. Concurrent efforts to raise awareness of the importance of proper sanitation and to promote hygiene and sanitary education will help people to understand the importance of improved sanitary conditions, will create demand and support for the project, and will increase people's willingness to pay for the system's operation and maintenance.

The capital costs of sewerage networks and wastewater treatment systems are often financed by central and local governments, sometimes with the support of international cooperation agencies. However, once the treatment plant has been built, the responsibility for its operation and maintenance rests with municipal authorities and the community itself, which must muster sufficient financial resources for this purpose. A system's O&M costs are covered mainly by user fees, which should reflect actual costs and must meet the approval of the community before the system can be implemented. The reuse of effluent may prove to be an additional source of financial resources.

The plant operator could be a community member contracted by the organization responsible for management of the system. Alternatively, a private, small-scale entrepreneur could operate the system. Although the O&M activities of constructed wetland systems are relatively simple, the plant operator must receive adequate training. During the start-up phase and first months of operation, the technical support provided by experts from a trained nongovernmental organization (NGO), consulting firm, or university would help to overcome initial operational difficulties. Furthermore, experience indicates that emptying the sedimentation tank of sludge and the clogged filter material are critical activities that usually require technical assistance from local authorities.

Costs of SSHF constructed wetland schemes

As revealed by the experience in Central America, the capital costs of subsurface horizontal flow constructed wetland schemes range from US$50 to $100 per person served by the system, including pretreatment, the primary treatment units, and the constructed wetland itself (see also table 3.3 in chapter 3).[24] These costs are mainly influenced by the cost of land and of transport for transferring the filter material to the construction site. The capital costs of SSHF constructed wetland schemes are similar to those of other extensive treatment technologies. Apppendix D contains a table the compares the construction (and O&M) costs of selected technologies.

The annual O&M costs range from US$2 per capita (La Providencia, Leon, 2,800 people) to $5 per capita (Masaya pilot plant, 1,000 people), which includes a full-time operator.[25] Proceeds from reuse of the effluent and sale of plants grown on the surface of the constructed wetland could help to recover part of the O&M costs.

Apart from the costs of constructing, operating, and maintaining the infrastructure, it is important to budget for the “software” components of a constructed wetland project. The components include activities such as hygiene promotion, environmental education, capacity building, and community organization and mobilization, especially in the case of community-managed projects.

Reusing effluent and biosolids

During the dry season, water is scarce in the Pacific region of Central America. In Nicaragua, where the majority of crops are produced on the Pacific plains, farmers use untreated wastewater discharged to drainage channels to satisfy their demands for irrigation water, taking advantage of the free water source and the remaining nutrients. However, several species of enteric pathogens pose significant health risks to the farmers, communities, and consumers exposed to the untreated wastewater and crops irrigated with untreated wastewater. SSHF constructed wetlands reduce pathogen levels to some extent, which is described in more detail in this section.

The sludge generated in wastewater treatment plants—or the solids accumulating in the primary treatment unit (settling tanks) in constructed wetland schemes—can be used as a soil conditioner after the appropriate treatment.[26] Low-cost treatment may consist of sun drying in thin layers and prolonged storage on a roof-covered plot; dewatering and drying in sludge drying beds with subsequent storage; or dewatering in sludge drying beds and later composting with organic domestic or market waste (Koné and Strauss 2004).

Microbiological effluent quality of SSHF constructed wetlands in Central America

Efficiency of thermotolerant coliforms removal. Thermotolerant coliforms are commensal bacteria of the human intestine. They are used as an indicator of

[24] These values include pretreatment, primary treatment units, constructed wetlands, and sludge drying beds. The costs of other infrastructure (such as sewerage systems and pumping stations) and of social intervention (such as mobilizing the community and promoting good hygiene) are not considered.
[25] Values are based on Central American socioeconomic conditions.
[26] The drying and storage periods required to achieve the pathogen levels recommended by the World Health Organization are listed in WHO (2006).

fecal contamination of water, as well as of residual bacterial, viral, and protozoal pathogen levels in treated wastewater. Investigations conducted at the Masaya pilot system over a monitoring period of several years revealed a 2 log (two orders of magnitude) removal of thermotolerant coliforms in the overall treatment system, resulting in a mean effluent concentration of just under 5 log units.[27] Thus the effluent of a SSHF constructed wetland still presents a considerable level of fecal contamination, which must be taken into account when defining health protection measures for effluent reuse. Further reductions can be achieved by decreasing the hydraulic surface loading rate (that is, incrementing the surface area of the wetland).

Efficiency of helminth removal. Helminths are pathogens that can cause diseases such as ascariasis and anquilostomiasis (hookworm). In areas where helminths are endemic, wastewater reuse might be an important route for their transmission because of their low infective dose and long survival times in sewage, crops, and soil. Enteric helminths are endemic to Central America. Unsanitary conditions and the tropical humidity favor their spread and survival, imposing a considerable disease burden on the population.[28]

Investigations carried out in Nicaragua confirmed the presence of a variety of helminth species[29] in the influent of several wastewater treatment systems (López and Suázo 2000). The mean concentration of helminth ova in the influent to the pilot constructed wetland of Masaya was 23 eggs per liter, which was reduced to a concentration of d" 1 egg per liter in the effluent of the treatment system. This value complies with the performance target for unrestricted irrigation, restricted irrigation, and localized (drip) irrigation of low-growing crops, according to WHO's guidelines for the safe use of wastewater, excreta, and grey water (WHO 2006). However, if *children under the age of 15* are exposed to these substances, WHO's guidelines call for additional measures, such as treatment to d" 0.1 egg per liter, protective equipment, or antihelminthic medication. In light of these recommendations, further investigations of helminth egg removals in full-scale constructed wetland systems would be warranted. Such investigations would shed light on the performance limits of constructed wetland systems with respect to stringent health-related effluent standards.

Reuse of effluent for crop irrigation

The microbiological effluent quality of a SSHF constructed wetland system, along with its remaining nutrients such as nitrogen and phosphorus, render the effluent of such a system suitable for crop irrigation, provided that additional health protection measures are taken and *verified*. These measures include confining the irrigation to the local area (the low content of suspended solids in the effluent allows the use of drip irrigation systems), restricting crops to those that high-growing or are cooked before eating, and suspending irrigation several days before harvest to allow pathogen die-off. Additional recommendations on health protection measures for effluent reuse drawn from the field experience at the Masaya pilot plant are listed in chapter 3.

[27] $7.5*10^4$ MPN (most probable number) per 100 milliliters, achieved after about a three-and-a-half day hydraulic retention time and application of areal loading rates, as shown in appendix B.
[28] Oakley (2005) reported arithmetic mean concentrations of 9–744 helminth eggs per liter in the influent of 10 stabilization pond systems in Honduras.
[29] Predominantly roundworm (*Ascaris lumbricoides*).

3. Experiences with subsurface horizontal flow constructed wetlands

Central America

Masaya, Nicaragua

In 1996 the Austrian Development Agency introduced constructed wetland technology to Nicaragua by financing the implementation of a SSHF constructed wetland system. Located in the outskirts of the city of Masaya, Nicaragua, the system is treating the domestic wastewater (100 cubic meters per day) generated by some 1,000 people. The scheme comprises pretreatment (screen and grit tank), an Imhoff tank as the primary treatment unit, and four constructed wetland beds fed in parallel. The area of each wetland bed is about 350 square meters, totaling 1,400 square meters.

The system was intensively monitored for nine consecutive years by a team of engineers from a consulting firm and the Universidad Nacional de Ingeniería (UNI). It served as a demonstration plant, and the investigations carried out led to the determination of design criteria for local conditions. A variety of local plant species—such as common reed (*Phragmites australis*); elephant grass (*Pennisetum purpureum*), a fodder crop typical of Central America with high water and nitrogen demand; cattail (*Typha domingensis*); and reed canary grass (*Phalaris arundinacea*)—were planted on the surface. The different types of filter media used, such as volcanic gravel and rock, provided a large surface area for the attached growth of microorganisms, adequate filtration capacity, and high physical and chemical resistance.[30]

The quality of the treated domestic wastewater met the national Nicaraguan standards for the discharge of treated wastewater to the environment and for effluent reuse except for thermotolerant coliforms. Table 3.1 compares the results of the rigorous monitoring with the national standards for wastewater irrigation.

SSHF constructed wetland system at Masaya, Nicaragua.
Source: Proyecto Biomasa, 1997.

[30] For details, please refer to appendix B and Platzer et al. (2002).

Table 3.1 SSHF Constructed Wetland Effluent Quality, Masaya Pilot Plant, Nicaragua

Parameter	Raw wastewater	Imhoff tank effluent	SSHF CW effluent[a]	Removal efficiency, SSHF CW only	Removal efficiency, entire system	National effluent limits[b]:discharge to water bodies / *reuse for crop irrigation*
pH	6.8	-	7.1	-	-	6.5 – 8.5
BOD_5 (mg/L)	270	92	6	93%	98%	90 / *120*
COD (mg/L)	653	249	35	86%	95%	180 / *200*
Total suspended solids (mg/L)	251	59	7.5	86%	97%	80 / *120*
Nitrogen total (mg/L)	34	34	22	33%	33%	-
Phosphorus total (mg/L)	6.1	5.5	4.5	18%	27%	-
E. coli (MPN/100 ml)	1.6×10^7	3.5×10^6	7.0×10^4	1.7 log	2.4 log	1.0×10^3 / *1.0×10^3*
Helminths (N/1,000 ml)	23	-	< 1	-	>1.4 log	- / *1*

Sources of data: Platzer (2003); Platzer, Cáceres, and Fong (2004); Proyecto Astec (2005).
Note: Data are based on six years of consecutive monitoring (1996–2002). Between three and eight random samples (12 hours) were taken per year and analyzed in a recognized laboratory.
[a] Applied hydraulic surface loading ranged between 75 and 95 liters per square meter per day for the subsurface horizontal flow constructed wetland. The corresponding BOD_5 and suspended solids (SS) areal loading rates are given in appendix B. The annual average air temperature was 26.5°C, and wastewater temperatures ranged between 26 and 29°C.
[b] According to MARENA (2000).

The following main conclusions can be drawn from the experience:

- The SSHF constructed wetlands performs very efficiently in the removal of organic matter, suspended solids, and helminths, but is only moderately efficient in removing medium thermotolerant coliforms. Nutrients such as nitrogen and phosphorus are removed only to a minor extent.
- Filter material must be chosen carefully, avoiding fine fractions to prevent clogging. Every two to two and a half years on average, parts of the (volcanic) filter material just behind the inlet distribution zone becomes clogged and must be replaced.
- Stormwater runoff from heavy rainfalls must be prevented from entering the filterbeds to avoid the deposition of fine material on the wetland surface.
- Pollution loads of organic matter and suspended solids must be limited to guarantee the long-term treatment performance of the wetland without colmatation (see appendix B for applied and recommended loading rates).
- As a rule of thumb, 1.3–1.5 square meters of wetland surface per person equivalent is sufficient under *Nicaraguan* conditions.
- A well-trained operator can handle the plant. However, technical support is needed to empty sludge from the settlement tank and replace the clogged material.
- The system should be fenced off to avoid theft and entry of unauthorized persons.
- The treatment scheme does not cause unpleasant odors or provoke the proliferation of mosquitoes.

Effluent from the pilot plant in Masaya was used to irrigate a variety of crops in order to study the presence of pathogenic microorganisms in the dry seasons of the years 1997–2002. The concentration of nutrients in the effluent of the scheme enabled crop development without the need for artificial fertilizers. The studies demonstrated that the effluent did not affect the soil structure, and it permitted irrigation of crops with medium salt tolerance.

The crop species investigated included species growing below the surface such as onion, beetroot, manioc, and peanut; species in partial contact with the soil such as zucchini and cucumber; and species growing close to the surface such as tomato, beans, paprika, and fruit trees (papaya). In addition, elephant grass, a plant used in Nicaragua as cattle fodder, was grown on the surface of the constructed wetland.

Irrigation trials were conducted to determine the microbiological quality of the crops and crop yield, applying furrow irrigation during the dry season, suspending irrigation at least one week before harvesting, and washing crops with clean water prior to analysis as additional safeguards.

Microbiological contamination of the crops through the reuse of the effluent varied according to the type of crop and its contact with the soil or treated wastewater.[31] In general, plants growing below the surface, such as onion and beetroot, had the highest level of fecal contamination. Peeling the crops greatly reduced pathogens on the crop surface. Leaves of elephant grass grown on the surface of the constructed wetland did not show any fecal contamination because of the subsurface flow.

Crops such as beans, sweet corn, and sugar cane produced yields similar to those irrigated with well water and receiving applications of chemical fertilizers. By contrast, yields of rice, paprika, and tomato irrigated with the effluent of the constructed wetland were poorer because of their higher nutrient demand. Finally, the elephant grass grown on the surface of the constructed wetland demonstrated good production rates compared with those of the elephant grass irrigated with well water.

Elephant grass used for cattle fodder in Nicaragua.
Source: Proyecto Astec, 2005.

Applying furrow irrigation at Masaya.
Source: WSP, 2006.

Irrigated crops at Masaya, Nicaragua.
Source: WSP, 2006.

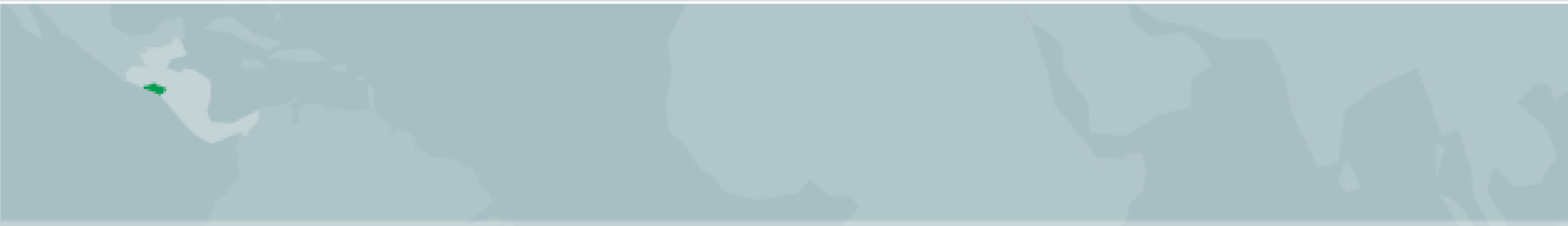
[31] For more details, see Platzer, Cáceres, and Fong (2004).

The following recommendations[32] on health protection measures are drawn from the field experiences in Masaya:

- Restrict irrigation
  - to crops that are cooked before eating such as beans, manioc, sweet corn, and rice, because the cooking process deactivates the pathogens
  - to industrial crops that undergo a drying, roasting, or extraction process such as sugar cane, peanuts, and soybeans
  - to high-growing crops such as fruit trees (for example, papaya and citrus—orange, lemon, mandarin, grapefruit, etc.)
  - to nonfood plants such as ornamental flowers, fodder plants, or bamboo, which can be used as construction material.
- Use nonsurface irrigation techniques such as low-cost drip irrigation systems to protect farmers and nearby communities and to optimize the use of irrigation water.
- Plant elephant grass as an alternative plant species on the *surface* of the constructed wetland. Elephant grass has high growth rates, does not become contaminated because of the subsurface flow conditions, and can be sold as cattle fodder.
- Suspend irrigation at least one week before crop harvesting.
- Ensure that workers avoid hand-to-mouth contact during farm work (such as during cigarette smoking).
- Organize awareness campaigns that promote good hygiene, emphasizing handwashing with soap. Such campaigns should accompany wastewater irrigation programs and target farmers and their families, consumers, and communities close to irrigated fields.
- Urge responsible authorities to verify all the health protection measures applied and to certify crops from hygienically safe production. However, because farmers often prefer to cultivate cash crops such as lettuce, controlling and enforcing crop restriction might prove difficult.

As for sludge management, in Masaya septic sludge was removed periodically from the settling tank, discharged to a simple sludge drying bed, and left for sun drying for several months. The completely dry solids were then deposited under fruit trees on-site. Analysis of the pathogen concentrations in the dried sludge has not been conducted.

[32] These recommendations include comments by Silva (1999), Platzer (2003), and M. Strauss, personal communication, 2007.



San José Las Flores, El Salvador

San José Las Flores, a village in northeastern Chalatenango, El Salvador, is an outstanding example of community participation in a sanitation project and community-based management of the sanitation system.

In 1986, when the original settlers returned to their village after the civil war, gastrointestinal infections broke out, killing many children. Poor sanitary conditions were mainly responsible for the outbreak. In response, the highly organized and motivated inhabitants implemented a sanitation project with financial and technical support from the Swiss Agency for Development and Cooperation (SDC) and the local NGO Pro-Vida. The project included community development, intensive hygiene promotion, construction of a sewerage system for the most densely populated part of the village, home to126 families or about 650 persons, followed by construction of a wetland system and on-site sanitation (latrines) for the remaining population. The community actively participated in the implementation of the systems under the coordination of a local committee.

The social process of technology adoption. The project began in 1997 with the election of the Municipal Water and Environmental Sanitation Committee. These community members promoted the project and defined and organized community participation. Meanwhile, hygiene promoters, trained by the NGO, conducted door-to-door visits and organized meetings to raise awareness and educate village inhabitants.

Community participation in key decisions such as the type and location of the treatment system empowered the community to contribute actively to the sanitation project. The constructed wetland system proposed—and eventually accepted by the community—was based on the experience of the pilot plant in neighboring Nicaragua. Reasons for adopting the technology included its simple O&M requirements and low recurrent costs, the availability of construction materials, the stable treatment process, and the good treatment performance.

Treatment performance. The constructed wetland system in San José Las Flores was designed by the consulting team at UNI in Nicaragua, using the parameters established at the Masaya pilot plant. As a result, the treatment performance of the new system was that of the system in Nicaragua (see table 3.2). The effluent essentially meets the national effluent standard of El Salvador, except for fecal coliforms, which would require additional retention time (that is, a larger constructed wetland bed).

Management of the treatment system and technical assistance for O&M. The constructed wetland system has been managed by the local committee, which appointed a plant operator. SDC covered O&M costs for the system's first two years of operation. Since then, tariffs have been collected from the community to pay the plant operator. Experience from Masaya and from San José Las Flores indicate that the simple O&M tasks do not require the services of highly skilled technicians; rather, they can be carried out by a community member after adequate

Table 3.2 **Effluent Quality of SSHF Constructed Wetland System, San José Las Flores, El Salvador**

Parameter	Raw wastewater	Effluent	National discharge limits
BOD_5 (mg/L)	482	15	30
COD (mg/L)	880	53	60
Suspended solids (mg/L)	663	22	60
Fecal coliforms (MPN 100/ml)	2.8×10^6	3.5×10^3	1.0×10^3

Source of data: Aguasan COSUDE (SDC) and Pro-Vida (2003).
Note: Samples were taken only occasionally. Information on the applied hydraulic loading rate was not available.

Constructed wetland at San José Las Flores, El Salvador.
Source: SDC, 2003.

training by experienced personnel. Ideally, the operator should visit a similar treatment system to learn the routine activities. The operator of the San José Las Flores system was trained at the pilot plant in Nicaragua.

Although constructed wetland systems do not tend to present difficult problems that require specialized knowledge, experience suggests that technical assistance by experts will help to ensure the successful operation and management of the plant. This assistance is especially required during the first few months after start-up and during major O&M activities, such as removing sludge from the septic tank or replacing clogged parts of the filter media. In San José Las Flores, the community operator trained members of the local committee and a member of the youth group to avoid operating problems during his absence. The NGO provided technical support for emptying sludge from the septic tank[33] and monitoring the effluent quality of the treatment system.

[33] According to the SDC, the local committee planned to reuse the dried septic sludge as soil conditioner. Details on the operation of the sludge drying bed were not available.

Other experiences in Central America

The successful operation and satisfactory performance of the pilot plant in Nicaragua encouraged dissemination of the technology and led to the construction of several plants in the region, mainly for the treatment of domestic and municipal wastewater (see table 3.3).[34]

Table 3.3 SSHF Constructed Wetlands for Domestic and Municipal Wastewater Treatment in Central America

Treatment plant	Location	Start-up date	Design flow (m^3/day)	Design capacity (persons)	Specific surface area (m^2/person)	Investment costs (US$)	Unit costs (US$/person)	Management
Family house	Managua (N)	2000	1	6	2.0	1,650	275	Owner
Hospital, Masachapa	S. Rafael del Sur (N)	2001	7.2	72	1.8	7,400	103	Hospital staff
Salinas Grandes	León (N)	2002	30 (grey water)	300	1.1	24,400	81	Community
Los Sabogales	Masaya (N)	2006	160	846	1.1	50,000	59	NGO
Pilot plant	Masaya (N)	1996	100	1,000	1.3	42,000	42	Operator: university
San José Las Flores	Chalatenango (ES)	2000	180	1,365	1.5	68,500	50	Community
Masatepe	Masaya (N)	2002	220	2,200	1.2	126,000	57	Utility
La Providencia	León (N)	2000	418	2,780	1.2	116,000	42	Municipality
Teupasenti	Danlí (H)	2001	365	2,800	1.5	92,000	33	Community
Chichigalpa	Chinandega (N)	2005	910	8,750	1.3	400,000	46	Utility

Source of data: Proyecto Astec (2005).
Note: N = Nicaragua; ES = El Salvador; H = Honduras.

[34] In Nicaragua, constructed wetland systems have also been used as tertiary treatment units for agroindustrial wastewater from slaughterhouses and dairy plants.

Site visits to several treatment systems in 2005 revealed the following situation:

- At Masachapa's hospital in Nicaragua, difficulties in the management of the local water supply system resulted in permanent water shortages. Therefore, the constructed wetland received only a limited wastewater flow.
- The sanitation system at Salinas Grandes, Nicaragua, consists of dry sanitation toilets with urine separation. The grey water is recollected and treated in the community-managed constructed wetland. However, apparently adequate capacity building and community organization have not been pursued effectively during the implementation process, and technical assistance for sludge emptying has not been granted. Lack of ownership, interest, and time by the community members has resulted in very limited operation and maintenance of the plant. Nevertheless, the constructed wetland still performed well at the time of the visit.
- The system at Los Sabogales near Masaya, Nicaragua, only recently began operations after standing unused for several years because of a delay in the housing program, which left the wastewater plant without any influent. Recent information, however, indicates that the plant is now in operation and is being maintained by a local NGO, which contracted a specialized plant operator.
- The systems at Masatepe and Chichigalpa, Nicaragua, constructed under a program of the European Union, are now operated by the public water company in charge of urban sanitation infrastructure. The plant at Masatepe is operating well and is demonstrating good treatment performance. In Chichigalpa, the staff responsible for O&M at Central America's currently biggest constructed wetland system was, at the time of the visit, lacking the equipment needed for appropriate plant operation even several months after the start-up because of the financial constraints of the utility. However, the final effluent quality of the constructed wetland appeared to be satisfactory.
- The plant installed in the small neighborhood of La Providencia in the city of Leon, Nicaragua, is managed by the municipality and has been performing well for several years. However, O&M has not been carried out on a continuous basis because of the limited resources of the municipality.
- The system at Danlí, Honduras, is managed by a community committee whose members are very enthusiastic. The plant performed well at the time of the visit four years after the construction. However, important maintenance activities such as sludge emptying of the septic tank have not been carried out for years, leading to a very high sludge level in the tank.

The state of operations and management observed at the majority of the treatment systems reveal the importance of adequate coordination of all stakeholders; sound financial arrangements that include levying a fee for sewer connections and operation of sewerage and treatment systems; and the appropriate management and technical assistance to ensure long-term sustainability. At many installations, operation and maintenance have not been carried out as required because of lack of financial resources, insufficient involvement of communities and local authorities, and planning processes that often do not account for long-term O&M. Nevertheless, several constructed wetland schemes showed good effluent quality because of the robustness of the systems.

South America

Constructed wetland schemes have increasingly come under examination for use for domestic wastewater and grey water treatment in several South American countries. The following sections describe some applications of such schemes in Peru, Colombia, and Brazil. These descriptions are drawn from a recent regional study commissioned by the World Bank's Water and Sanitation Program from experiences presented during a workshop in Lima in August 2007 and from the author's further research.

Lima, Peru

After its experience with a pilot plant installed at the National University of Engineering, the government of Peru installed three SSHF constructed wetland schemes in the arid outskirts of Peru's capital.[35] The treatment systems, finished in late 2006, were part of an overall water and sanitation project of the Ministry of Housing, Construction and Sanitation at El Mirador–Pachacutec in Lima's Ventanilla district.

Each constructed wetland scheme serves about 2,500 people and includes a manual screen, grit separators, and sedimentation tanks as pretreatment steps for the domestic wastewater before it enters the wetland, which is composed of two units of the SSHF type. A covered underground sludge storage tank with a perforated bottom and side walls is provided for dewatering septic sludge generated in the primary sedimentation tanks.

All treatment schemes operate under gravity flow conditions and are located between the settlement and the coastline; the wetland sites are cut into the steep, sandy slopes of the terrain. The filter material is made up of coarse gravel to prevent clogging and an upper layer of sand to allow root penetration of the local emerging plant species, cattail (*Typha domingensis*). A pipe has been installed in the inlet zone of each wetland to allow periodic flushing and cleaning.

Constructed wetland units at Ventanilla, Lima.
Source: Maldonado (2007).

[35] In addition to the described project, a variety of similar projects (mostly on a smaller scale) have been carried out in Lima and other regions of Peru. The Pan American Health Organization (PAHO) has elaborated an inventory of constructed wetland systems in Peru as of 2007.

As for treatment performance, the constructed wetland scheme removes more than 95 percent of organic contamination (in terms of BOD) and reduces the concentrations of thermotolerant coliforms by 2–3 log units, according to recent analyses (see table 3.4). Compared with design assumptions about wastewater flow, the influent flow seemed to be low during a visit to the site in August 2007. This situation could explain the good pathogen removal.[36]

At the time this report was being prepared, the implementation of a simple irrigation system was under way, with the goal of reusing the treated effluent for reforestation purposes. Furthermore, the responsibility for operation and maintenance of the systems was being transferred to Lima's water utility, Servicios de Agua Potable y Alcantarillado de Lima (SEDAPAL), which also was handling O&M of the condominial water and sewerage network of El Mirador–Pachacutec. SEDAPAL was planning to finance the required activities out of its annual O&M budget for infrastructure maintenance. The users of the installed treatment plants were not being charged any fees for O&M of the treatment schemes. The population has been sensitized, however, to the correct use of the (condominial) sewerage system, such as separating garbage and household chemicals, which will also contribute to trouble-free operation of the biological treatment system in the future. Awareness was raised among the users about the health and environmental benefits of the treatment plants in order to strengthen users' sense of responsibility and prevent vandalism.

Table3.4 **Summary of Project Parameters, El Mirador–Pachacutec, Lima, Peru**

CWscheme	Design population (inhabitants)	Design flow[a] (m^3/d) [L/s]	Total size ofSSHF CW (m^2)	Total BOD removal performance[b]			Thermotolerant coliforms removal performance[b]			Construction costs[c] (US$ per capita)
				Inlet (mg/L)	Outlet (mg/L)	Removal (%)	Inlet (mg/L)	Outlet (mg/L)	Removal (log units)	
Sector I	2,655	106 [1.54]	3,200	696	9	> 99	9.2×10^7	1.4×10^5	2.8	
Sector II	2,610	104 [1.51]	3,200	845	< 4	> 99	4.3×10^6	4.5×10^3	3.0	$68
Sector III	2,295	92 [1.33]	3,200	590	9	> 99	1.6×10^8	2.6×10^5	2.8	

Source: Summarized from Maldonado (2007).

[a] Wastewater production of 40 liters per inhabitant was assumed in the design. Data on actual flow measurements were not available.

[b] According to a single analysis per constructed wetland scheme (February 2007).

[c] Forty percent of these costs are associated with excavation works.

This experience in Lima will be an important reference for future projects, taking into account a holistic, decentralized concept providing water, access to networked sewerage, relatively small treatment plants, and effluent reuse in periurban settings. It remains to be seen whether SEDAPAL will be able to carry out O&M activities as required, including sludge removal from the settlement tanks and the appropriate disposal of biosolids. Apart from wastewater treatment, the main function of the constructed wetlands, they act as green islands in the midst of the desert landscape of Peru's capital. Moreover, they provide a green barrier during windy weather, holding back sand blown from the coastline toward the settlement.

Scaling up constructed wetland schemes in Peru will require further investigations of the appropriate filter media available in different locations of the country, along with detailed performance data on the described system.

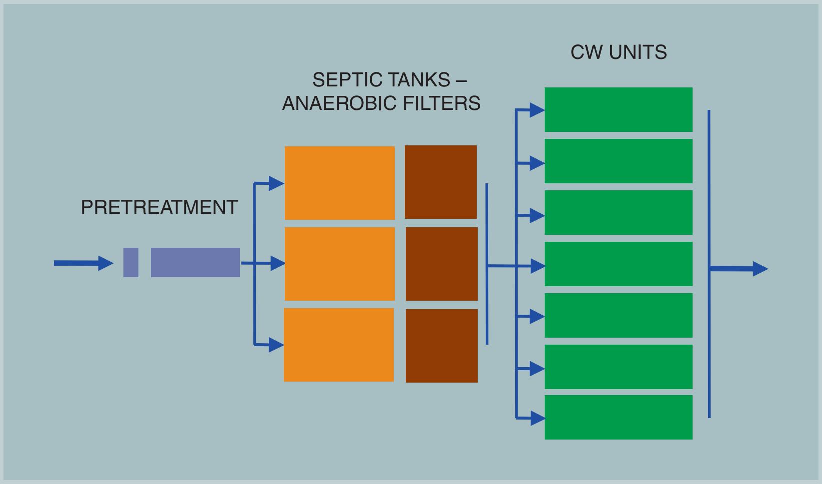
[36] The effluent was not analyzed for helminths.

Pereira, Colombia

Much like in Peru, a university spearheaded development of constructed wetland technology in Colombia, starting with small-scale laboratory investigations. Experiences gained in the laboratory trials were then applied by a team of enthusiastic staff at the Universidad Técnica de Pereira (UTP), Pereira's technical university, at the existing wastewater treatment plant, "La Florida," as part of a sanitation project to mitigate the negative environmental impacts on the Otún river basin. The system of "La Florida" originally consisted of a pretreatment unit and a combination of a septic tank and anaerobic filter, treating wastewater arising from a nearby small community (see figure 3.1). But the efficiency of the system was low, possibly because groundwater infiltration of the sewerage system diluted the wastewater, resulting in low influent concentrations of several contaminants.[37] According to UTP, this phenomenon occurs quite often in rural settlements of Colombia. The effluent of the system did not comply with Colombian legislation, which calls for more than 80 percent BOD_5 removal.

Among other rehabilitation measures, several SSHF constructed wetland units were added as tertiary treatment units and operated in parallel to resolve the problem. Different filter media and local plant types also were selected for the constructed wetlands, which then were operated under relatively high organic loading rates[38] and short retention times (less than one day). Careful monitoring revealed that constructed wetland units with fine sand (0.3 millimeters) as filter media initially performed well in removing organic pollutants (50–70

Figure 3.1 Layout of Treatment Scheme, "La Florida," Pereira, Colombia



Source: Adapted from Villegas Gómez et al. (2006).

[37] According to data provided by Villegas Gómez et al. (2006) and the author's calculation, about 280 persons are connected to the treatment plant, producing a flow of 1.85 liters per second (160 cubic meters per day), which translates into a theoretic daily wastewater production of 570 liters per capita.

[38] Approximately 11.5–15 grams of BOD_5 per square meter per day (115–150 kilograms per hectare per day). For further details, see Villegas Gómez et al. (2006). Recommended organic loading rates are about 50 percent lower (see appendix B).

percent) and bacteria (up to 2 log units of fecal coliforms). However, they quickly clogged up, resulting in surface flow. The constructed wetland units with gravel as filter media had lower removal performance in terms of organic contamination, but did not present operational problems.[39]

SSHF constructed wetlands for tertiary treatment in Pereira, Colombia. Source: WSP (2007).

A member of the local community is in charge of O&M of the system. UTP staff provide technical guidance, and they carried out the investigation and monitoring of the treatment system. The investigation revealed that the overall treatment system, including the constructed wetland units, was meeting the requirements of the Colombian legislation, and thus the combination of septic tank, anaerobic filter, and constructed wetlands were, in principle, adequate for polishing of effluents from anaerobic treatment stages. As mentioned in previous sections, great attention must be given to ensuring the adequate granulometry of the filter media, as well as to limiting hydraulic and contaminant surface loading to prevent clogging of the wetlands.

Pasto, Colombia

The SSHF constructed wetland system in Pasto, a municipality in southern Colombia, was implemented in 2006 through a joint effort of the municipality, the local utility EMPOPASTO, and the NGO Semillero de Sueños (see table 3.5). The wetland scheme, which was constructed with engineering assistance from a Colombian university, comprises various pretreatment and primary treatment units, followed by a single relatively small constructed wetland. According to the NGO, the treatment system is designed to receive the wastewater of about 1,000 inhabitants of a nearby community. The filter material is composed of fine gravel and organic soil. The local community is using the treated effluent for crop production.

The NGO, which also relies on the services of professional sanitary engineers, carried out important social work with the population. Activities included participatory analysis of priorities to achieve better health and environmental protection, consultation with community leaders, hygiene promotion, and environmental education

[39] As stated earlier, selection of the appropriate filter media and application of a limited hydraulic loading rate are key to avoid clogging, a primary cause of collapse of constructed wetlands. See the recommended loading areal loading rates in appendix B.

aimed at achieving a high degree of community ownership, as well as effective management of the plant by community members.

Much like in San José Las Flores in El Salvador, the social intervention of the NGO has produced very positive results in terms of "empowering" the local population to take care of the plant and to consider the treated effluent as a valuable resource for crop production. It is therefore highly recommended that community mobilization be a component of constructed wetland projects for community-based systems. It is also important to consider the cost of social interventions in the planning phase of the project.

Table 3.5 **Project Data of Constructed Wetland Scheme, Pasto, Colombia**

Design flow (m^3/d)	Design population	Dimensions, w x l (m)	Area (m^2)	Construction costs (US$, 2006)
112	1,000	9 x 17.5	157	$14,500[a]

Source: K. Moncayo, personal communication, 2007.
Note: The technical sustainability of the wetland system has yet to be verified, because the dimensions seem very small compared with the design flow and required hydraulic capacity, respectively.
[a] Excludes costs for the social intervention.

SSHF constructed wetland in Pasto, Colombia, during construction.
Source: K. Moncayo, personal communication, 2007.

Santa Catarina State, Brazil

Several small constructed wetland projects have been implemented since 1990 in the state of Santa Catarina in southeastern Brazil. SSHF constructed wetland schemes have been installed predominantly in rural settings as a decentralized wastewater treatment option for a variety of institutions.

A team composed of engineers from two universities in Santa Catarina[40] and Empresa de Pesquisa Agropecuária e Extensão Rural (EPAGRI), a state company for agricultural research and rural development, was involved in implementing several constructed wetlands at the state company's own training centers. The SSHF constructed wetland treatment schemes (Agronômica, Videira, Tubarão, and São Joaquim), which use septic tanks as primary treatment, were designed for a population of 50–150 persons. Coarse sand is used as filter media, and the wetlands are planted with a local wetland plant and operated under subtropical climate conditions by EPAGRI staff (Philippi et al. 2006). Clogging was reported for the Videira system after four years of operation. The average contaminant removal performance of the constructed wetland units are shown in table 3.6. The effluent of some of the systems receives further treatment in stabilization ponds and is used for aquaculture (fish farming).

Table 3.6 Average Removal Performance of Several SSHF Constructed Wetland Units Installed at EPAGRI Training Centers in Santa Catarina, Brazil

COD (%)	BOD_5 (%)	TSS (%)	*E. coli* (log units)	Average ambient temperature (°C)
69–98	73– 98	53–87	1–3	14–25

Source: Summarized from Philippi et al. (2006).
Note: Data refer to constructed wetland units only and do not take into account the primary treatment. Monitoring was performed monthly between October 2005 and May 2006.

Septic tank and constructed wetland installed at EPAGRI at Florianópolis, Santa Catarina, Brazil. Source: WSP (2007).

The systems have been successfully replicated for several other institutions of similar size in Santa Catarina, including a hotel with a capacity of 180 guests. At the time of the visit, hotel owners were thinking of reusing effluent for flower production. As at EPAGRI, the owners operate the plants at their own expense (WSP 2007).

[40] Departamento de Enenharia Sanitária, Universidade Federal de Santa Catarina, and Universidade do Oeste de Santa Catarina, Campus de Videira.

Alagoinhas, Brazil

The city of Alagoinhas, located about 150 kilometers north of Salvador in Brazil's tropical state of Bahía, has had some interesting and successful experiences in improving sanitation services through participatory approaches. In 2001 the first municipal conference on environmental sanitation, an initiative led by the local mayor, resulted in the development of the municipal policy for environmental sanitation. The policy called for creating a municipal sanitation plan, which was drafted with the technical assistance of the Federal University of Bahia within one year, following other successful examples from neighboring municipalities. The plan was developed in a participatory way, engaging civil society and other stakeholders in monthly public review meetings. The development of the environmental sanitation policy and the plan resulted in the implementation of various sanitation projects.[41]

In 2001 Serviço Autônomo de Água e Esgoto de Alagoinhas (SAAE), Alagoinhas's water and sanitation utility, initiated interventions in periurban areas, where sanitary conditions were worst. With the goal of improving health and environmental conditions in the city, SAAE implemented a series of condominial sewerage projects, replacing septic tanks that conveyed effluents to the stormwater drainage system and capturing household wastewater directly discharged to the streets.

Among the possible solutions for reducing the pollutant load in water bodies, constructed wetlands were identified as a natural treatment system, drawing on experiences with the systems designed by staff of Santa Catarina's universities. Because of the relatively simple construction and O&M activities required for such systems, SAAE decided to implement a constructed wetland as a biological treatment unit after a grit removal tank and an anaerobic reactor[42] in the barrio of Jardim Petrolar Alagoinhas (Castro Reis et al. undated). The plant was designed for a population of about 2,500. A summary of project parameters appears in table 3.7 and of the average removal performance of wastewater contaminants in table 3.8. According to the analyses provided, suspended solids and pathogenic bacteria were removed only to a limited extent, which could be a consequence of both the high hydraulic surface load applied and the very coarse filter media. The constructed wetland unit therefore predominantly reduced organic pollution, but levels of fecal contamination remained almost the same in the effluent of the plant. Thus the treatment system is contributing to environmental protection, but is not reducing health risks by eliminating pathogens.

Constructed wetland system at Jardim Petrolar, Alagoinhas, Brazil. Source: WSP (2007).

[41] For more information, see http://www.tni.org/docs/200701251751082475.pdf.
[42] A tank for biological wastewater treatment in the absence of oxygen.

Table 3.7 **Summary of Project Parameters of the Constructed Wetland Scheme at Jardim Petrolar, Alagoinhas, Brazil**

Flow rate (m^3/d) [L/s]	Connected population	Dimensions, w x l x d (m)	CW area (m^2)	Size of filter media (cm)	Hydraulicloading rate (m^3/m^2, d)	Construction costs (US$)
233 [2.7]	2,470	10 x 25 x 0.9	250	5–20	0.9	$27,000[a]

Source: Summarized from Castro Reis (undated).
Note: The applied hydraulic loading rate (HLR) is very high (about tenfold of the HLR applied at constructed wetlands in Central America). However, filter clogging was not reported, perhaps because of the very coarse filter media.
[a] Includes land costs.

Table 3.8 **Average Removal Performance of the Constructed Wetland Units at Jardim Petrolar, Alagoinhas, Brazil**

BOD_5 (%)	Suspendedsolids (%)	Fecal coliforms(log units)
73	61	< 1

Source: Adapted from Castro Reis (undated).
Note: Data refer to constructed wetland units only and were collected monthly during a six-month period in 2003.

In 2003 a second constructed wetland scheme was built in the neighborhood of Fonte dos Padres. It was composed of an Imhoff tank and a SSHF constructed wetland. SAAE has been operating and maintaining the plant; the municipality contracted with a private company for sludge removal from the septic tank.

4. Lessons learned and conclusions

Experiences with constructed wetland technology in several countries of Central and South America over the past years have provided the following lessons:

Subsurface horizontal flow constructed wetland systems are a feasible technical option for the treatment of wastewater from small to medium-size communities for the following reasons:

- The systems are characterized by a stable treatment process, robustness, and good contaminant removal, favored by the high ambient temperatures in tropical regions such as Central America.
- Operation and maintenance costs are low, stemming from the natural biological treatment process, low or no energy requirement, and lack of need to rely on sophisticated equipment, spare parts, or chemicals.
- The O&M requirements are relatively simple, which allows community management if adequate training and technical assistance are provided.
- The systems' environmental impact in terms of liquid, solid, and gaseous emissions is low.
- The systems are attractive in appearance.

The main limitations of constructed wetland technology, particularly of the subsurface horizontal flow type, are the following:

- They require more land than energy-intensive and highly mechanized technologies (at least 1.3–1.5 square meters of wetland area per person equivalent under Nicaraguan conditions).
- They require a relatively large amount of adequate filter material and sealing material, which must be available locally.
- Certain parts of the filter material clog up, requiring replacement of parts of the filter.
- Technical assistance is required for community-managed systems.
- Few mechanisms are currently in place with the responsible authorities to effectively control treatment operations and enforce standards.

Adequate water supply and wastewater recollection systems are a prerequisite for constructed wetland schemes:

- Certain prerequisites must be met when considering a constructed wetlands as an off-site wastewater treatment system for a community to ensure efficiency of the system. These include a well-functioning piped water supply system with household connections and an efficient sewerage system. The latter requires stormwater and solid waste management to operate effectively. Condominial systems could be considered to reduce investment costs.
- Development plans and coordination between responsible institutions, including donor agencies, are important to avoid the implementation of treatment systems before completion of other required infrastructure components.

Design and construction are not to be taken easily:

- Constructed wetland systems should be designed by experienced professionals, and the design should include adequate selection and sizing of pretreatment and primary treatment units. Especially in tropical regions, stormwater peak flows from heavy rains must be taken into account.
- A crucial component of a well-functioning SSHF constructed wetland system is the appropriate filter media, which should be fine enough to ensure good treatment performance. The material must not be overly fine, however, so that the system

maintains a sufficient long-term filtration capacity to avoid frequent clogging. Considerable care must be taken during the construction of the wetland to avoid later operational problems such as short-circuiting or surface flow conditions.

- Capacity building and training are required to ensure that local institutions and organizations can carry out these tasks. Design standards based on local experiences would help to disseminate the technology and to avoid basic design and construction errors.
- Several universities in the region are already acquainted with the design and construction principles. Networking should be encouraged to exchange lessons learned and to avoid repeated pitfalls or redundant efforts.

Sustainable operation and maintenance remains the primary challenge:

- In most Latin American countries, municipalities are responsible for providing water and sanitation services and managing treatment systems. When a municipality does not have this responsibility, the community must be organized to manage operation and maintenance of the system, as well as fee collection. This task will require building the capacity of community-based organizations and local authorities to manage the treatment plant successfully. Alternatively, small-scale private operators can be contracted to carry out O&M activities.
- Although the O&M activities of constructed wetland systems are relatively simple, the plant operator must receive training. Experience indicates that emptying sludge from the sedimentation tank and replacing clogged filter material are critical activities, which usually require technical assistance from local authorities or other institutions.
- During the start-up phase and first months of operation, if needed, experts from a trained NGO, university, or consulting firm can provide the technical support needed to overcome initial operational difficulties, but the costs of such support must be budgeted in the planning phase.
- Securing financial resources to operate and maintain the system will depend primarily on the capacity to generate revenues for the recovery of recurrent costs. To ensure that users fulfill their obligations, the responsible authorities and the users must agree on a tariff structure before implementing the system. This process must be based on users' willingness and capacity to pay, taking into account the economic situation of the beneficiaries and the guaranteed access of the poor to the service. Wastewater treatment fees are best tied to tariffs for water and sanitation services. Efficient service and ongoing awareness of health and environmental benefits will enhance the willingness of beneficiaries to pay. Reuse of effluent during the dry season could be serve as an additional source of incomee.

SSHF constructed wetlands as a wastewater treatment option constitute a health protection measure for the reuse of effluent:

- The reuse of treated wastewater can contribute to the sustainability of the treatment system. If the appropriate health and environmental protection measures and good agricultural practices are taken into account, the reuse of wastewater can help to conserve water, protect the environment, and generate income.
- Well-designed and -operated SSHF constructed wetland systems reduce the pathogenic microorganisms in the effluent, but the effluent still contains sufficient nutrients to allow plant growth without the application of artificial fertilizers.

- Although the efficiency with which such systems remove pathogenic bacteria such as thermotolerant coliforms is relatively well known, further investigations should be carried out on the removal of helminth eggs, which are an important public health hazard, especially in the reuse of effluent for crop production. Cooperation and partnerships between research institutions with specific expertise and institutions in the south should be encouraged for this purpose.
- Additional health protection measures—such as restricting crops to those that undergo cooking before consumption, are high growing, are industrial crops, or are nonfood plants; adhering to localized (drip) irrigation methods; and ceasing irrigation several days before harvesting—allow the reuse of the treated effluent for irrigation in accordance with WHO's guidelines for wastewater use in agriculture (WHO 2006). Authorities must establish the appropriate control mechanisms to avoid negative health implications, verifying effluent quality and implementing additional health protection measures.

Sludge arising from SSHF constructed wetland schemes is a potential resource:

- Generally, the sludge generated in treatment plants for domestic wastewater—that is, the solids that accumulate in the primary settling tank in SSHF constructed wetland schemes—poses considerable sanitary risks and must receive further treatment before final disposal.
- After appropriate treatment for dewatering, stabilization, and hygienization, the solid fraction (biosolids) of fecal sludges becomes a valuable soil conditioner (WHO 2006).
- Low-cost sludge treatment methods may consist of sun drying in thin layers and prolonged storage in a roof-covered area; dewatering and drying in sludge drying beds followed by storage; or dewatering in sludge drying beds followed by combined composting with organic domestic or market waste (Koné and Strauss 2004; M. Strauss, personal communication, 2007). WHO's guidelines provide infomation on the storage times required to deactivate pathogens.

Demand for the system and user participation are central to its success:

- In general, the implementation of constructed wetland systems for treatment of wastewater must be based on the genuine demand of users. Community mobilization, participation, and involvement in the important decisions made during the planning and implementation process are essential to ensuring the sustainability of the system.

Complementary actions increase the benefits of the intervention:

- Hygiene promotion and sanitary education campaigns are essential to increasing the public health benefits of a sanitation project, creating awareness and demand, promoting active community participation, and fostering willingness to pay for the services. In wastewater reuse projects, hygiene promotion is fundamental to preventing health risks to the operators, nearby communities, and consumers. NGOs are good partners to carry out these tasks. Costs for these social interventions must be budgeted during the planning phase of the project.

Appendixes

Appendix A: Routine operation and maintenance activities

Activities	Materials necessary	Frequency	Time required
Inlet channel with screen			
Clean filter	Bar screen and shovel	Daily	10 minutes
Clean accumulated solids at bottom of the channel	Shovel and wheelbarrow	Monthly	30 minutes
Measure influent flow	Flow meter	Hourly	5 minutes
Sand and grease trap			
Eliminate accumulated surface scum	Surface skimmer and wheelbarrow	Every 3 days	15 minutes
Extract sludge from the bottom	Drainage pipe, shovel, and wheelbarrow	Depending on accumulation of solids	30–40 minutes 1
Sedimentation tank			
Remove surface scumfrom vent area	Surface skimmer and wheelbarrow	Every 15 days	5 minutes
Extract accumulated sludge at bottom of tank	Drainage pipe or semisolid pump	Between 6 and 12 months	1 ½–2 hours
Humidify mulch of biogas filter	Pail or hose	Weekly	5 minutes
Change mulch of biogas filter	Shovel and wheelbarrow	Annually	15 minutes
Constructed wetland			
Eliminate sedimented solids in inlet channel	Shovel and wheelbarrow	Monthly	30 minutes
Cut the plants grown	Machete, rake and wheelbarrow	According to growth cycle	Yield: 50 m^2 of plant surface per person per day
Change top 1–2 meters of filter bed after the larger media of the distribution zone	Pick, shovel, and wheelbarrow; use new media of same granulmetry	When superficial water flow is noted	Yield: 1.5– 2 m^3 per person per day
Control water level within constructed wetland	Flexible hose	Daily	5 minutes
Sludge drying bed			
Remove stabilized sludge from sludge drying bed	Shovel and wheelbarrow	Every four months	3 hours
Improve condition of sludge if it emits bad odors	Shovel and lime	Daily	10 minutes

Appendix B: Technical design parameters

The following sections contain general design recommendations for SSHF constructed wetlands and design parameters as investigated at the constructed wetland at Masaya, Nicaragua (Platzer et al. 2002; Proyecto Astec 2005).

1. General design recommendations for SSHF constructed wetland (Brix and Arias 2007; H. Brix, personal communication, 2007)

- Wastewater flow must pass through the constructed wetland system without overland flow or flooding.[1]
- Operation should remain feasible in the likely event of changing hydraulic conductivity (partial colmatation).
- The constructed wetland shall be both drainable and floodable.
- Water levels within the system should be fully controllable through the use of inlet and outlet structures.
- The configuration must be adapted to the site in terms of project boundaries and hydraulic profiles.
- The recommended maximum difference in elevation between inlet and outlet water level is 0.3 meters.
- A bottom slope of about 1 percent is appropriate.
- At least two units should be installed.
- Large systems must be subdivided into several units to allow control of water flow and to avoid short-circuiting, according to the following recommendations:
  - The width of a constructed wetland should be limited to 20 meters to allow even water distribution across the entire width. The inlet channel should be subdivided, with separate water loading for wider units.
  - The maximum length of systems with a bottom slope of 1 percent should be limited to 30 meters to allow controlled flooding of the system (for example, for weed control, good plant growth, balancing fluctuations of flow rate).
- The recommended depth of the constructed wetland units is 60–80 centimeters.
- Coarse sand or gravel should be used as filter material with the following characteristics[2]:
  - $d_{10} > 0.3$ millimeters
  - $d_{60}/d_{10} < 4$.

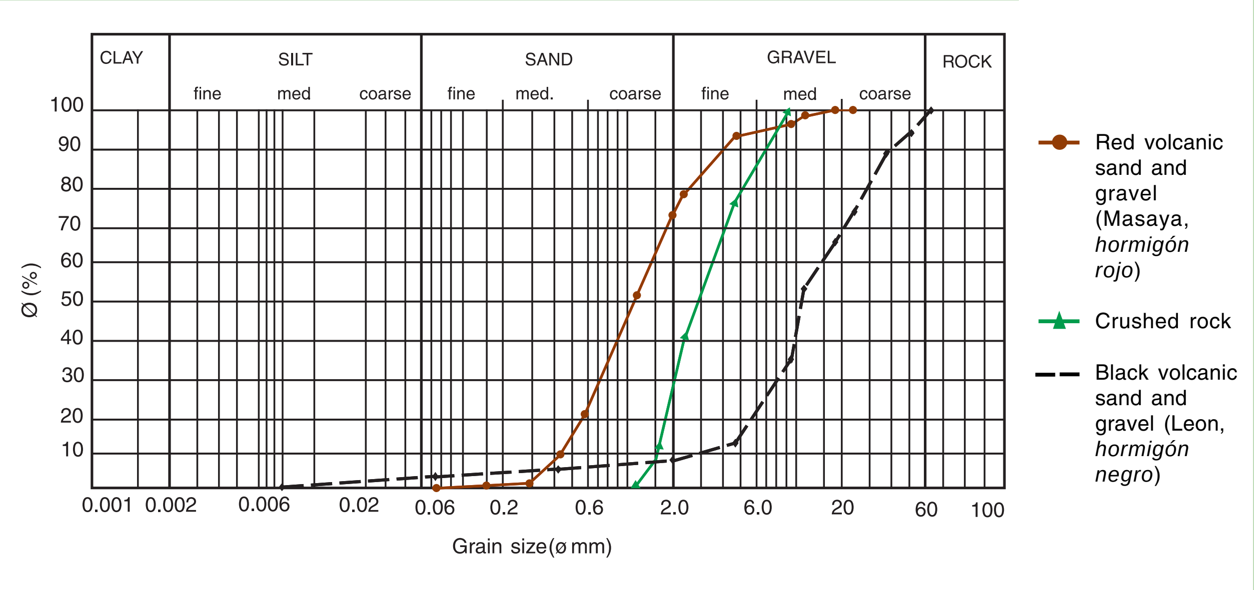
2. Applied filter material in Nicaragua (figure B.1)

- Type of main filter material: volcanic coarse sand and fine gravel, crushed rock
- Hydraulic conductivity k_f (before use): approximately $1.3–1.5 \times 10^{-3}$ meters per second
- Porosity e (before use): approximately 0.48–0.60

[1] Darcy's Law is normally used for the hydraulic design of the constructed wetland. A minimum cross-sectional area can be determined at a given flow rate, hydraulic conductivity, and hydraulic gradient—see USEPA (1999) for more information.

[2] To be determined through the elaboration of granulometric curves. See also USEPA (1999) for the estimated hydraulic conductivity of different filter media and grain sizes.

Figure B.1 Granulometric Curves of Filter Media Used in Nicaragua



Source: Proyecto Astec (2005).

3. Areal loading rates applied in Nicaragua

The areal loading rates (ALRs) of specific pollutants (grams per square meter per day) are calculated by multiplying the influent flow rate (cubic meters per day) by the respective influent pollutant concentration (milligrams per liter equal grams per cubic meter) and dividing by the surface area (square meters) of the SSHF constructed wetland (USEPA 1999).

The BOD_5 ALR and the suspended solids ALR are especially important in relation to the clogging of the SSHF constructed wetlands, because accumulating (bio-) solids can lead to colmatation. The following ranges and upper limits for these loading rates have been applied in Masaya, Nicaragua, to avoid frequent clogging. They are relatively *conservative values* that guarantee the long-term contaminant removal efficiencies stated in table 2.1 of this report. Replacement of clogged filter media is a critical and often neglected O&M activity, leading to unwanted surface flow conditions. Areal loading rates higher than the ones that follow could result in more frequent clogging of the filter media:

- BOD_5 areal loading rate: 6–8 grams BOD_5 per square meter per day
- SS areal loading rate: 4–6 grams SS per square meter per day

In both cases, the higher values refer to applications in tropical areas with high wastewater temperatures such as Central America. The values essentially match the recommendations in the international literature (USEPA 1999; García et al. 2002; Bécares 2004).

The areal loading rates just given can also be used to estimate the required area of the constructed wetland, if the maximum daily flow rate and average pollutant concentrations in the influent of the constructed wetland (that is, after the primary treatment unit) are known or estimated. In view of the existence of two criteria (BOD_5 and SS ALR), the more conservative value (that is, the larger surface area) must be selected—see USEPA (1999) for more information.

4. Ambient and wastewater temperatures at Masaya, Nicaragua

- Air temperature: 25.3–28.5°C
- Wastewater temperature: 26.0–28.8°C

5. Wetland plants applied in Masaya, Nicaragua

- Common reed (*Phragmites australis*)
- Cattail (*Typha domingensis*)
- Reed canary grass (*Phalaris arundinacea*)
- *Heliconia* species

6. Degradation constants determined for the Masaya pilot plant

The model based on first-order kinetics and plug flow conditions, usually used to estimate effluent quality for certain inlet concentrations of different pollutants under certain hydraulic loading rates, gives good results for organic contaminants in terms of BOD_5 and COD. The area-specific degradation constants k can be calculated using the following formula (Vymazal et al. 1998):

$$k = q_A * (\ln C_i - \ln C_{out})$$

k area-specific degradation constant (meters per year)
q_A hydraulic loading rate (meters per year)
C_i inlet concentration of the contaminant (milligrams per liter)
C_{out} outlet concentration of the contaminant (milligrams per liter)

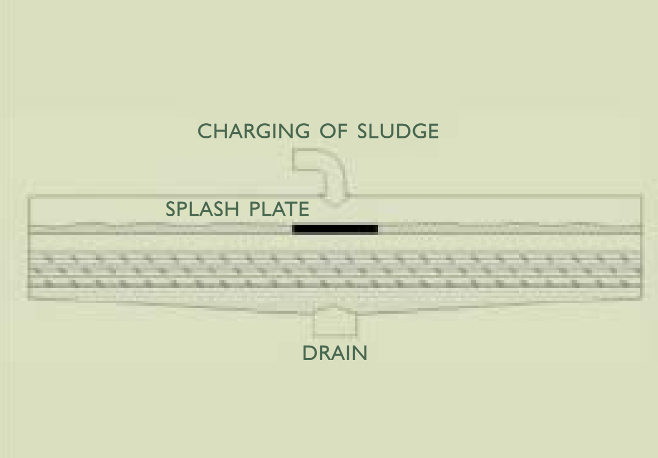
Under the conditions (1–5) just described, the empirically determined degradation constants k (mean ± 95 percent confidence limit) for BOD, COD, total nitrogen, and total phosphorus were as follows (Platzer et al. 2002):

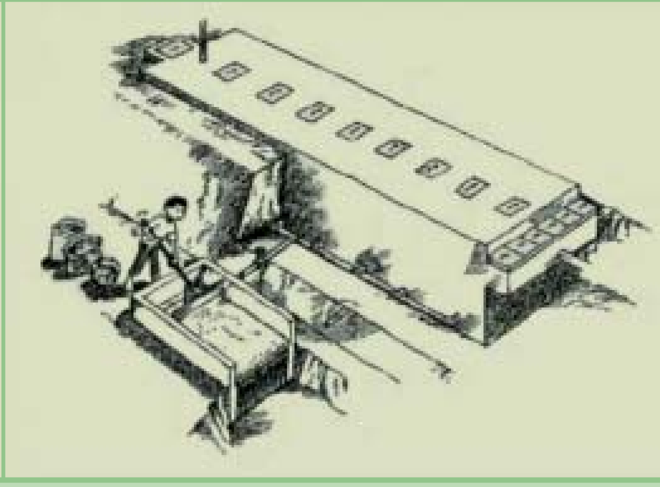
- k_{BOD} 81.8 ± 13 meters per year
- k_{COD} 60.8 ± 12 meters per year
- k_{TN} 11.8 ± 6 meters per year
- k_{TP} 6.9 ± 4 meters per year
- k_{SS} 61.0 ± 18 meters per year

However, it is essential to note that these constants have been determined under the given site-specific conditions, which, apart from air and wastewater temperatures, also take into account characteristics of the filter material used and specific flow characteristics, which are inherent to each constructed wetland. The rate constants can vary substantially between different systems.

Appendix C: Design principles of sludge drying beds

Description:	Sludge drying bed is one method for dewatering sludge through reduction of moisture content by filtration and evaporation. The bottom of the filter bed is laid with perforated pipes for draining the filtrate or seepage water. After drying, moisture content is reduced by 35% or less. Sludge drying beds are normally located near treatment plants to receive/treat the sludge produced by primary/secondary treatment.
Design:	0.21 - 0.58 m^2/capita of area requirements. Width of bed is usually 4 m and depth of sand and gravel layer is 70 cms average. 1-2 m^3 of sludge/m^2 of bed loading.
Applications:	Applicable where space is available. Most commonly used means for dewatering sludges.
Components:	Concrete structure for bed and walls; filter media (sand and gravel); splash block; underdrain system; inlet pipe.
Capacity:	For treatment plants serving a population of 1,000 up to 20,000.
Costs:	Investment lowest among sludge dewatering methods. O&M: No other cost except for labor.
Utility & Efficiency:	Dried sludge is not fully disinfected, but solid content is increased to 50-70% total solids.
Reliability:	Reliable during dry sesason, but efficiency decreases during wet season.
Flexibility:	Good process flexibility.
Reapplication **Potential:**	Have good potentials for implementation by communities and/or local government.
Regulatory/ Institucional Issues:	• Requires a work force for operating and maintaining the facility.
Operating Principles:	Sludge is applied to the beds in 20 cm depth or layer. Drying take place due to evaporation and filtration or percolation. The dried sludge is removed manually and applied for agricultural use or sold as organic compost. The filtrate, however, needs to be treated further.
Maintenance:	1. Replacement of sand every 6 months or 1 year 2. Prevent weed and grass encroachment 3. Regular dried sludge removal
Construction Materials:	1. Concrete walls 2. Sand and gravel 3. Cast iron (CI) or polyvinyl chloride (PVC) pipes 4. Asphalt paved sludge beds
Advantages:	1. Simple to operate 2. Lowest cost option among sludge dewatering methods 3. Energy-saving
Disadvantages:	1. Filtrate/seepage water has to be treated 2. Requires solar power 3. May produce odor and flies nuisance





Source: *Philippines Sanitation Sourcebook and Decision Aid* (WSP et al. 2005).

Appendix D: Economic considerations for selected wastewater treatment technologies

Technology	Land requirements (square meters per person)	Consumed power (watts per person)	Liquid sludge to be treated (liters per person per year)	Dewatered sludge to be disposed of (liters per person per year)	Construction costs (US$ per person)	O&M costs (US$ per person per year)
Primary treatment (septic tanks)	0.03–0.05	0	110–360	15–35	$12–20	0.5–1.0
Constructed wetlands	***3.0–5.0***[a]	***0***	-	-	***20–30***	***1.0–1.5***
Overland flow	2.0–3.5	0	-	-	15–30	0.8–1.5
Anaerobic pond + facultative pond	1.2–3.0	0	55–160	20–60	12–30	0.8–1.5
Anaerobic, facultative, and maturation pond	3.0–5.0	0	55–160	20–60	20–40	1.0–2.0
Septic tank + anaerobic filter	0.2–0.35	0	180–1,000	25–50	30–50	2.5–4.0
UASB reactor +maturation ponds	1.5–2.5	0	150–250	10–35	15–30	1.8–3.0
Conventional activated sludge	0.12–0.25	18–26	1,100–3,000	35–90	40–65	4.0–8.0
Low-rate trickling filter	0.15–0.3	0	360–1,100	35–80	50–60	4.0–6.0
Rotating biological contactor	0.1–0.2	0	330–1,500	20–75	50–60	4.0–6.0

Source: Adapted from Sperling and Chernicharo (2005).
[a] Net area requirements for the SSHF constructed wetland type as used in Nicaragua are about *1.5 square meters per person* as described in chapter 2 of this document.

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Weblinks for further information

- **CEMAGREF (French research institute in agricultural and environmental engineering)**
  Link to a guide (in French) on constructive wetland technology as used in France, elaborated by French water agencies, research institutions, and private companies.
  http://www.lyon.cemagref.fr/qe/epuration/documents/Guide-Macrophytes.pdf

- **IW:LEARN (International Waters Learning Exchange and Resource Network)**
  Link to the Constructed Wetlands Community of Practice anchored at the International Waters Learning Exchange and Resource Network of the Global Environment Facility (GEF). The site provides links to further information on constructed wetlands, including events, training courses, and GEF-funded projects and activities.
  http://www.iwlearn.net/abt_iwlearn/pns/partner/constructedwetlands

- **SANDEC (Department of Water and Sanitation in Developing Countries), Swiss Federal Institute for Environmental Science and Technology (EAWAG)**
  The site provides relevant information and publications on fecal sludge management (including sludge drying beds and constructed wetlands for septage treatment) and on a variety of other topics.
  http://www.eawag.ch/organisation/abteilungen/sandec/publikationen/publications_ewm/index_EN

- **USEPA (U.S. Environmental Protection Agency)**
  Link to design manuals, technology assessments, and other literature on constructed wetland technology (for applications specifically in the United States).
  http://www.epa.gov/owow/wetlands/watersheds/cwetlands.html

- **WSP publication on constructed wetlands (in Spanish)**
  http://www.wsp.org/filez/pubs/biofiltro.pdf

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