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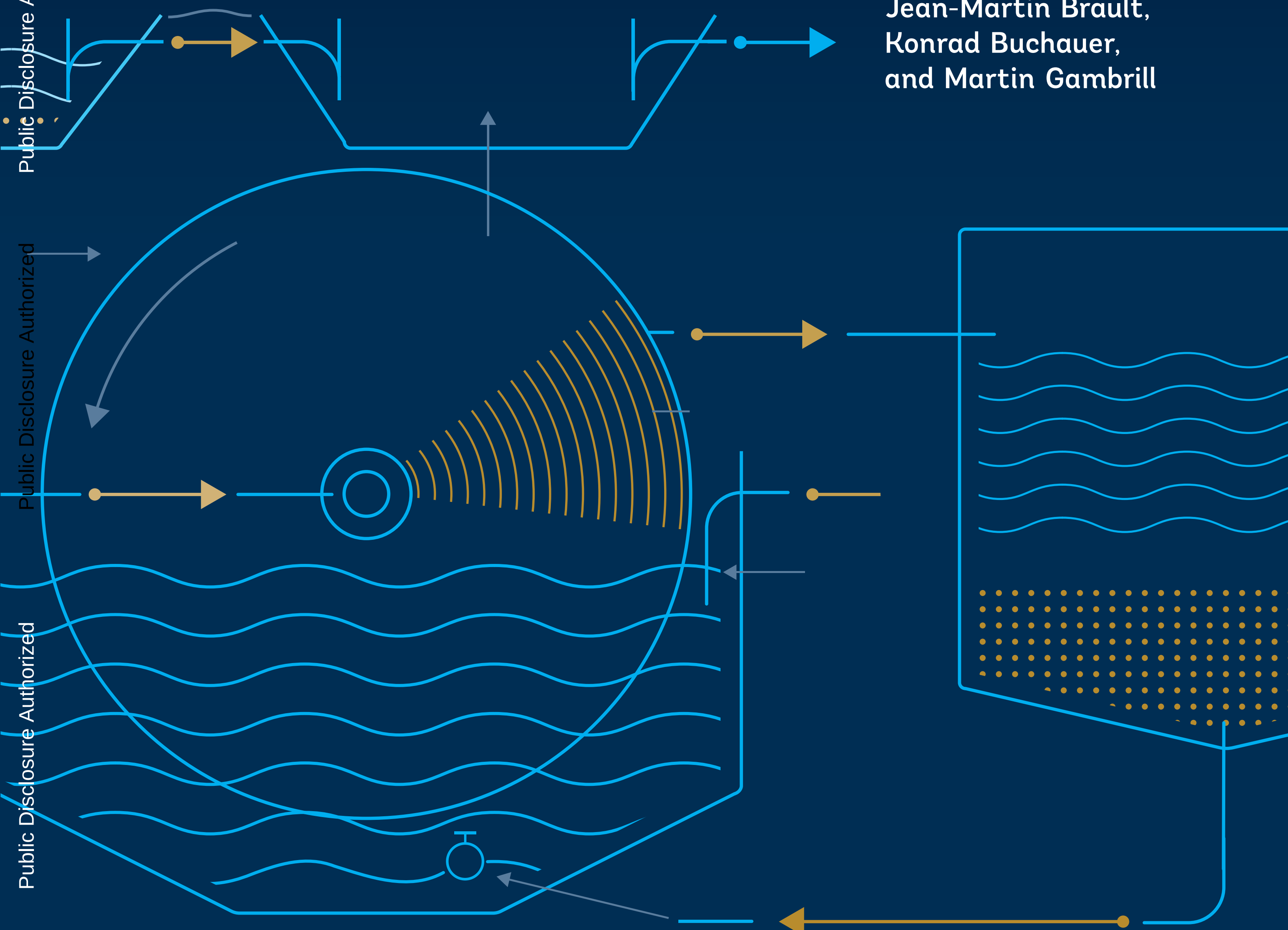
WATER GLOBAL PRACTICE

WASTEWATER TREATMENT AND REUSE

A Guide to Help Small Towns Select Appropriate Options

Jean-Martin Brault,
Konrad Buchauer,
and Martin Gambrill



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Executive Summary

Small towns in low- and middle-income countries (LMICs) are growing rapidly and struggling to meet the increased demands of wastewater collection and treatment. To avert public health crises and continued environmental degradation, small towns are actively seeking safely managed sanitation solutions, appropriate for their scale, institutional capacity, financial resources, and overarching needs. This document is designed to provide a guide of small-town wastewater treatment processes in order to assist engineers, managers and other stakeholders responsible for wastewater service provision in identifying and selecting appropriate wastewater treatment processes for small towns. This guide is part of a World Bank suite of tools and other material to support World Bank teams and their government counterparts in the planning, design, and implementation of sanitation projects in urbanizing areas.

Addressing the specific context of small towns, the format of this guide begins with an introduction of key concepts for a decision maker to understand and then applies a suggested five-step approach to exploring appropriate wastewater treatment technologies, culminating with case studies from three regions applying this approach. The guide's introduction delves into the unique considerations for small-town wastewater treatment and the exploration of corresponding technologies. Before demonstrating the application of the approach, the guide also navigates (a) factors external to the technologies that define the characteristics and environment of a given small town and that will affect technology choice, coupled with (b) technology-specific information that will ultimately influence decision making. Before embarking on the formal planning and design process, the user is highly encouraged to become familiar with the guide methodology in its entirety while drawing on the principles of the Citywide Inclusive Sanitation (CWIS) approach.[1] Sewers and wastewater treatment should be pursued only in small towns where such a service-delivery approach is deemed the most appropriate, following the comparison of its advantages and disadvantages with onsite sanitation and fecal sludge management alternatives, as espoused by the CWIS approach.

Note

1. For more information about the Citywide Inclusive Sanitation approach, see the World Bank's CWIS website at www.worldbank.org/cwis.

Abbreviations

ABR	anaerobic baffled reactor
AL	aerated lagoon
ANDA	Administración Nacional de Acueductos y Alcantarillados
ANF	anaerobic filter
AS	activated sludge
AT	aeration tank;
BAF	biological aerated filters
BD	biogas digester
BNR	biological nutrient removal
BOD	biochemical oxygen demand
cap	capita
CAPEX	capital expenditures
CAS	conventional activated sludge
CEPT	chemically enhanced primary treatment
CH_4	methane
Cl	chlorine or chlorination
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalents
COD	chemical oxygen demand
CW	constructed wetland
CW(1-st)	single-stage constructed wetland
CW(hybrid)	hybrid constructed wetland
CWIS	Citywide Inclusive Sanitation
DBP	disinfection by-products
EA	extended aeration (= low-load activated sludge)
FAB	fluidized aerated bed
FC	fecal coliforms
F/M	food to microorganism ratio
FSM	fecal sludge management
FST	final sedimentation tank
GHG	greenhouse gas
GWP	global warming potential
IFAS	integrated fixed film activated sludge
IMH	Imhoff tank
ISF	intermittent sand filter
LMIC	low- and middle-income countries
MBBR	moving bed biological reactor
MBR	membrane bioreactor
MLD	million liters per day (1 MLD = 1,000 m^3/d)
MLSS	mixed liquor suspended solids
MPN	most probable number
N_2O	nitrous oxide
NPV	net present value
O&M	operation and maintenance
ONEE	Morocco's National Electricity and Water Office (Office National de l'Électricité et de l'Eau Potable)
OPEX	operating expenditures
PE	population equivalent
PE60	population equivalent of 60 g BOD_5 per capita per day
P&ID	piping and instrumentation diagram
PP	polishing pond
PST	primary sedimentation tank
RBC	rotating biological contactor
RDF	rotary disc filter
RF	rock filter
SBR	sequencing batch reactor
SDG	Sustainable Development Goal
SF	sand filter
SpTP	septage treatment plant
SS	suspended solids
ST	septic tank
TF	trickling filter
TF/SC	trickling filter/solids contact process
THM	trihalomethane
TSS	total suspended solids
UASB	upflow anaerobic sludge blanket reactor
UASB-TF	UASB followed by a TF
UASB-WSP	UASB followed by a WSP
UV	ultraviolet [disinfection]
WSP	waste stabilization pond (here consisting of the classical configuration of anaerobic, facultative, and maturation ponds)
WWTP	wastewater treatment plant

About This Guide

1

Introduction and Background

Low- and middle-income countries (LMICs) generally lack adequate wastewater infrastructure, and although 39 percent of the global population used a safely managed sanitation service in 2015, only 27 percent of the global population used facilities connected to sewers that led to wastewater treatment plants (WHO and UNICEF 2017). This gap between collection and treatment varies across regions—for example, 69 percent of the wastewater collected in Arab States is safely treated (LAS, ESCWA, and ACWUA 2016), compared with 30 to 40 percent in Latin America (Rodriguez and others 2020) and roughly 10 to 20 percent in Asia and the Pacific region (UNESCO World Water Assessment Programme 2017). This gap is important because it poses a critical obstacle to reaping the benefits of improved human health, environmental protection, and water security, particularly as wastewater is increasingly seen as a valuable resource that should be managed effectively. Investment needs associated with closing this gap are substantial, contributing to the need for a paradigm shift with respect to wastewater planning, management, and financing. There is a need for adaptive solutions that can be incrementally implemented, building off what is already in place.

This paradigm shift is particularly relevant for countries dealing with rapid urbanization. In these countries, small towns create a unique challenge as they exist at the nexus of urban and rural dynamics and can thus play a strategic role in bridging the gap between wastewater collection and treatment. For this to happen, appropriate wastewater treatment solutions should be selected to allow small towns to cope with the challenges of providing services without the potential for economies of scale offered in larger urban centers, and with the limited human and financial resources that are often found in small towns but which need to be considered when assessing the operation and maintenance (O&M) requirements of treatment plants.

Identifying appropriate wastewater treatment solutions for small towns in LMICs requires thinking beyond the conventional technologies applied in developed contexts and requires an understanding of how local constraints on human and financial resources, road connectivity and/or available inputs, such as chemicals and replacement parts, could influence technology choice. Although ultimately technology recommendations and designs will be the responsibility of a technical specialist or consultant, those responsible for wastewater service provision—engineers, managers and decision makers more broadly—should oversee this selection process and have the necessary information to discriminate between different treatment trains.

This guide was inspired by a report, "Definition of a Tool for Evaluating Unconventional Wastewater Treatment Technologies," commissioned under the World Bank-financed Oum Er Rbia Sanitation Project to provide Morocco's Office of Electricity and Drinking Water (Office National de l'Électricité et de l'Eau Potable [ONEE]) with a decision-making tool to diversify its menu of technological options for small towns as part of the rollout of the country's National Sanitation Master Plan. This guide has complemented the evaluation criteria proposed therein to highlight the priorities of wastewater treatment for small towns and aims to bring a more global perspective to the associated challenges (Golla 2014). In adapting the criteria used in the Morocco report, the guide relies on available data and publications from developed countries that the authors consider relevant to LMIC contexts. The peer review process also allowed for practitioners working in LMICs to provide inputs on the applicability and relevance of the guide's recommendations and its methodology in these contexts.

Objective and Target Audience

The objective of this guide is to assist engineers and managers responsible for wastewater service provision in understanding which solutions are technically feasible and in line with the priorities of their small town. It provides a methodology for these decision makers to identify the characteristics of their service area that will be most important in choosing appropriate wastewater treatment solutions and to understand the trade-offs between different solutions that meet their needs. The information presented in this guide therefore aims to support decision makers in reviewing the work of an engineering consultant but not to supplant the work of such a consultant.

The guide highlights key factors in the decision-making process, such as treatment facility design, possibilities for reuse, and receiving water quality. The comparison of technologies considers several priorities, including minimizing investment costs and ensuring operational sustainability.

Scope and Limitations

Although the guide details a methodology to determine appropriate wastewater treatment processes for small towns, it does not aim to provide a definitive answer as to which wastewater treatment technology would be "optimal" for a given small town. The reader should be mindful about the variability of contexts and the interpretation of the different aspects explored.

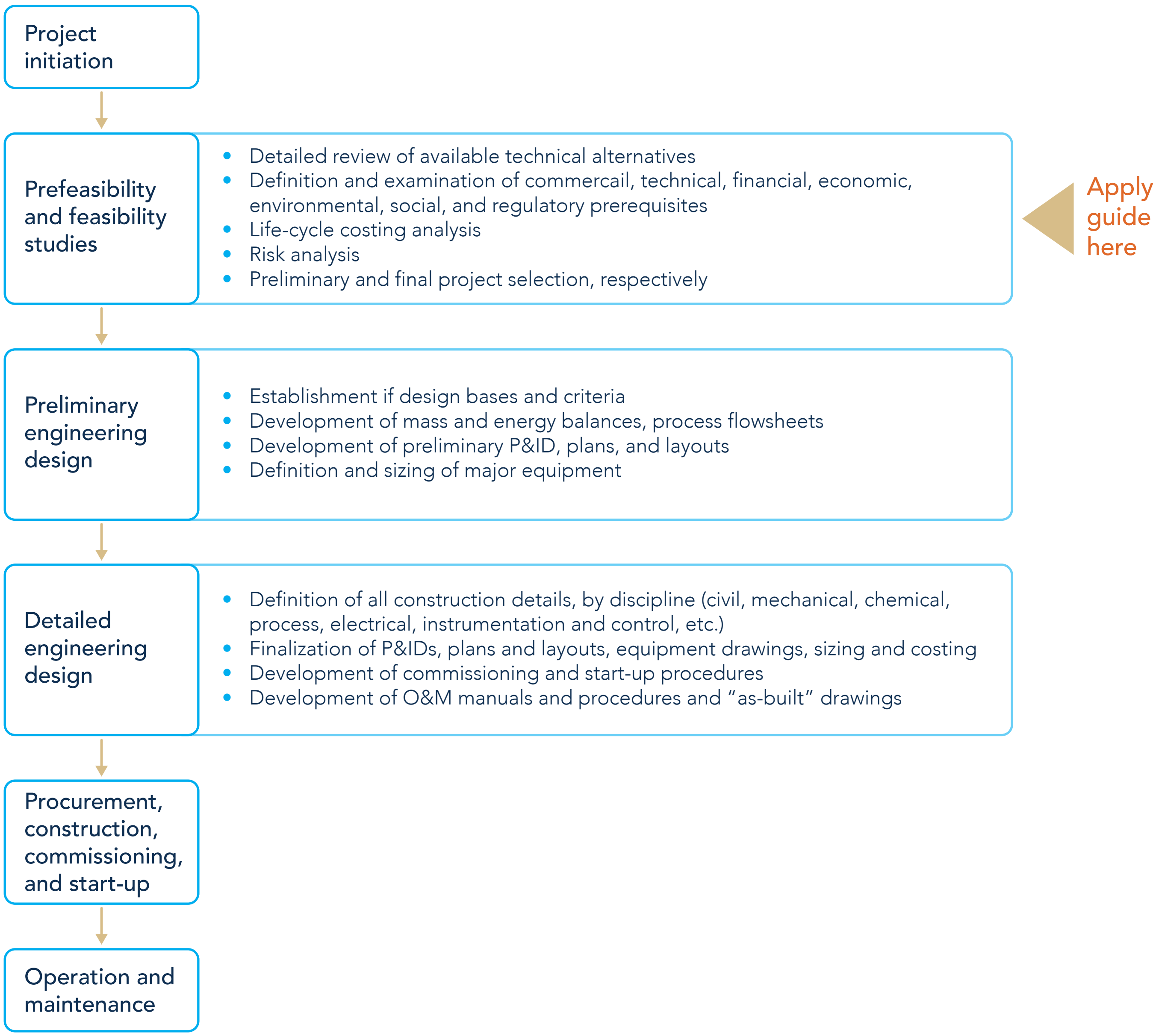
As a result, it is likely that, after applying the methodology proposed in the guide, more than one appropriate solution will be identified and a more detailed analysis (particularly regarding costs) may be necessary to further narrow down the selection. A more experienced user of the guide may still wish to include other technologies for additional comparison. The user should evaluate these additional technologies with the same criteria that are applied in the guide so as to be able to compare them with the technologies preselected here. Furthermore, the guide does not provide specific guidance on, or standards for, the engineering design of each technology, as a large number of such resources already exist.[1]

The guide emphasizes opportunities for cotreatment of wastewater with fecal sludge, where appropriate, although it does not provide guidance on fecal sludge management (FSM) or treatment.[2]

How to Use This Guide

This guide supports decision making in the prefeasibility and feasibility phases of a project cycle, as illustrated in Figure 1.1. Thus, the guide is meant to help optimize, at a very early project stage, when such optimization is easiest and most effective, the direction and the content of subsequent more detailed analysis.

FIGURE 1.1
When to Apply This Guide



Note: O&M = operation and maintenance; P&ID = piping and instrumentation diagram.

Overview of the Guide's Structure

Chapter 1 describes the guide's purpose, target audience, contents and organization, and provides guidance to the reader on how to use it.

Chapter 2 presents specific considerations to understand the context of small-town wastewater treatment. This section introduces the concept of a small town and presents the unique challenges of wastewater service provisions in such settings. Chapter 2 also presents wastewater resource recovery considerations for small towns.

Chapter 3 introduces basic concepts of wastewater treatment technology for small towns. This section addresses different wastewater treatment levels incorporated in a treatment train and presents individual technology sheets for the different technologies considered appropriate for small towns, as well as presenting appropriate treatment trains.

Chapter 4 builds upon the foundational knowledge in the prior chapters and delves into the factors influencing the choice of small-town wastewater treatment solutions. It identifies specific criteria that should be employed when using the guide. Criteria are split into those that are specific to a given town or context (project criteria) and those that relate to technology (technology criteria).

Chapter 5 applies the suggested five-step methodology to identify the appropriate wastewater treatment solution in a given small town, drawing on the theory and background provided in the prior sections. It details the aim of each step and the corresponding process to employ in carrying out the step.

Chapter 6 provides examples of the guide's application through the use of three case studies from Morocco, Vietnam and El Salvador.

The Citywide Inclusive Sanitation Approach

The World Bank Water Global Practice, in partnership with sector partners, have together advanced an approach to tackling urban sanitation challenges termed Citywide Inclusive Sanitation (CWIS). This comprehensive approach aims to shift the paradigm regarding urban sanitation interventions by promoting a range of technical solutions that help ensure that everyone has access to safely managed sanitation. The CWIS approach promotes a range of technical solutions—both onsite and sewers, centralized or decentralized—which are tailored to the dynamics of the world's burgeoning cities and their large pockets of informality by integrating financial, institutional, regulatory and social dimensions, and by harmonizing the sanitation solutions with related urban services, including water supply, drainage and solid waste management.

As part of the implementation of these CWIS principles, the World Bank is developing a suite of tools and other material[3] to support Bank teams and their government counterparts when engaging on CWIS initiatives. This suite of tools and other material are intended for use by World Bank task teams and their government counterparts for the planning, design, and implementation of urban sanitation projects, and they may also be of use to others working on sanitation challenges in urban areas around the world.

Notes

1. See, for example: (a) G. Chen, G. A. Ekama, M. C. M. van Loosdrecht, and D. Brdjanovic, *Biological Wastewater Treatment: Principles, Modelling and Design* (London: IWA Publishing, 2020); (b) S. R. Qasim and G. Zhu, *Wastewater Treatment and Reuse: Theory and Design Examples* (Boca Raton: CRC Press, 2018); and (c) Metcalf and Eddy, *Wastewater Engineering: Treatment and Reuse*, 4th ed. (New York: McGraw-Hill, 2003).
2. For more information on FSM, see, for example, the Fecal Sludge Management Alliance at https://fsm-alliance.org/ and L. Strande, M. Ronteltap, and D. Brdjanovic, *Faecal Sludge Management-Systems Approach for Implementation and Operation* (London: IWA Publishing, 2014). For fecal sludge treatment plant design, see K. Tayler, *Faecal Sludge and Septage Treatment: A Guide for Low and Middle Income Countries* (Rugby: Practical Action Publishing, 2018), https://practicalactionpublishing.com/book/693/faecal-sludge-and-septage-treatment.
3. For more information about the CWIS approach, see the World Bank website at www.worldbank.org/cwis.

Considerations for Small-Town Wastewater Treatment

2

Definition of a *Small Town*

Although there is no universally agreed upon definition of a small town, in most countries there is an understanding (formal or otherwise) of what areas to classify as small towns, which are typically based on population size and density.

The lower bound for the population of a small town is typically between 2,000 and 5,000 people, though in some areas (especially in Asia), the lower bound can be as high as 10,000 residents. The upper size limit varies even more, from 20,000 to 50,000 to as high as 100,000 people (again, the latter limit is found mostly in Asian countries). The population densities in small towns also vary widely: In Niger, for example, the average small town population density is14 people per square kilometer, whereas in Bangladesh it is 1,033 people/km^2 (Economic Consulting Associates 2015). Table 2.1 shows examples of the population ranges for small towns in different regions. These values were drawn from legal definitions and from data from World Bank staff.

Some definitions of small towns include additional criteria. For example, small towns may be defined as having certain key pieces of infrastructure (for example, types of public buildings or roads) or an average household income above or below given values. Geographical location can also differentiate small towns from other urban centers, as small towns are geographically more remote and are more separated from major markets than are primary or secondary cities. Nevertheless, small

TABLE 2.1
Population for Small Towns, by Country and Region

REGION	COUNTRY	POPULATION
Africa	Benin	2,000–20,000
	Ethiopia	2,000–60,000
	Mozambique	2,000–100,000
	Uganda	5,000–25,000
Asia	Bangladesh	25,000–200,000
	India	10,000–50,000
	Indonesia	10,000–100,000
	Philippines	10,000–100,000[a]
Europe	Eastern Europe	2,000–10,000
Latin America and the Caribbean	Bolivia	2,000–20,000
	Ecuador	12,000–50,000
	Haiti	3,000–10,000
	Honduras	5,000–30,000
	Nicaragua	2,000–50,000
	Peru	2,000–30,000
North Africa	Morocco	10,000–50,000
	Tunisia	2,000–50,000

[a] In the Philippines, the definition further specifies that small towns are places where people are mostly not farming, where it is not a predominant activity, and where the population density is greater than or equal to 500 people/km^2.

towns are often well connected to major roads and/or waterways, giving them better access to markets and other urban centers than rural areas. Although small towns typically have access to markets (for both buying and selling goods), it may take longer to get to these markets, and the cost of goods may consequently be higher than in larger urban centers. Their comparative remoteness also means that small towns typically have fewer highly trained technical professionals. Additionally, small towns cannot generally take advantage of existing service provision from large cities, such as the main electricity grid or their water supply and sanitation services.

Small towns targeted by this guide also tend to be closer to rural areas and thus to agricultural fields. This aspect of small towns is important for several reasons. First, such small towns often serve as a central location for collecting food before sending it to larger markets, making agriculture key to their economies. Second, these small towns are close to an ideal market for end-use products of wastewater treatment systems (treated wastewater for irrigation, biosolids for fertilizer, and so on). In addition, combined with collected animal waste, these wastewater end-use products offer increased options for biogas production. More broadly, small towns are often closer to natural resource extraction activities, such as mining—and, like agriculture, the mining sector provides another possible market for end-use materials (for example, reusing treated wastewater). Overall, as with most urban areas, the economies of small towns can be diverse, though they are often dominated by one of the aforementioned sectors.

Finally, please note that the definition of small towns presented in this guide excludes rural villages with populations below the ranges stated above for small towns, and excludes periurban areas surrounding major urban centers and large cities.

Common Characteristics of Small Towns Relevant for Wastewater Management

In most parts of the world, urban areas, including small towns, are growing faster than rural areas. In small towns with high growth rates, planning on traditional time scales can be challenging, and towns often struggle to keep pace with their growing populations. These fast growth rates call for more flexible and adaptive urban planning to allow for continued expansion of the population and of the town more broadly (for example, any industrial expansion).

This adaptive approach to planning can be particularly challenging in small towns, where institutions are often less developed. This is especially true in agglomerations that have only recently grown large enough to be considered a town. In these areas, water supply and sanitation may have historically been managed by community boards, but these models may no longer be appropriate. Where utilities do exist, they are often newer and less established. However, a wide range of institutional models exists, from community-run systems to centralized management handled by a nearby larger town. To have sufficient institutional capacity (especially in terms of technical skills) and to more generally use economies of scale, it may make sense to link multiple nearby small towns together. Legal institutions and frameworks may also be less evolved, which can affect the development of guidelines for both wastewater treatment and reuse—if reuse is to be permitted at all.

In small towns already experiencing industrial growth, the institutional framework selected for treatment plant operation will undoubtedly be affected by the choice of treatment technology, and vice versa, because the roles of regulation and monitoring will increase if industrial wastewater is also collected and treated. Additionally, the type of industry in a small town may affect not only the treatment technology but also possible markets for product reuse. For example, both the mining and agricultural sectors may use treated wastewater, but the water quality standards for each will differ, as will the capacity and skillset required to produce, monitor and enforce them.

At present, small towns use a wide range of technologies for managing sanitation. This variation is mostly explained by the different status of sanitation services in small towns in LMICs. Some small towns still have high rates of open defecation, whereas others may fully rely on onsite solutions (for example, latrines and/or septic tanks) or count on a single centralized sewer system. This guide focuses specifically on wastewater treatment, thus excluding any small town using only onsite sanitation. Nevertheless, although the guide focuses on contexts in which sewers are the dominant technical solution for conveyance of waste (that is, sewered collection of blackwater and graywater), the treatment technologies presented here may still be appropriate for small towns handling sewage combined with a certain amount of fecal sludge/septage (see "Fecal Sludge/Septage" in Chapter 4).

Wastewater Resource Recovery

The ability to recover resources generated in wastewater treatment plants (WWTPs) has become increasingly important in recent years, as several treatment by-products can have significant economic value for the utility or for the small town in the vicinity of a treatment plant, and as awareness grows regarding the importance of circular economy approaches in development. The evaluation of wastewater treatment alternatives for a given context should consequently always assess potential demand for and supply of these resources. The proximity of certain economic activities to a small town can help map and assess demand for reuse products, which are differentiated under the following broad categories:

1. *Water*, consisting of wastewater effluent treated to a level appropriate to the end use, such as for groundwater recharge, for irrigation of parks and lawns or of agricultural crops, for industrial processes, and so on
2. *Sludge*,[1] such as reuse as a soil amendment or as a fuel
3. *Nutrients*, through the treated wastewater effluent or the treated biosolids[2]
4. *Energy*, through the conversion of biogas into electric power and/or thermal heat, and through the combustion of processed solids (when these are converted into fuel briquettes) instead of fossil fuels

For example, nearby agricultural activity could represent a reuse market for treated wastewater effluent and biosolids, or it could also present the opportunity to carry out the codigestion of agricultural waste with the sludge from the WWTP. Alternatively, a mining company may be interested in the treated effluent from a small town's WWTP to use directly in its processes.

In addition, when considering the recovery of wastewater treatment by-products, it is important to assess the expected production or supply of reuse products in a realistic manner. Treatment plants tend to be oversized, and it can take many years, even decades, to achieve the design flow. This, in turn, can result in the much smaller production of treated wastewater effluent, biogas and biosolids than the amount originally planned for. Smaller than expected by-product outputs result in oversized reuse structures, generate less revenue, and can cause a project to fail. These negative outcomes are especially likely in biogas recovery projects, in which designers often tend to blur the thresholds between the potential for biogas generation and the amount of biogas that can indeed be captured for reuse, resulting in a financial burden for the sustainability of the related infrastructure. A realistic estimate of treatment by-products is also important in estimating the potential income generation from the sale of these by-products.

The evaluation of wastewater treatment alternatives should also take the existing legal and institutional framework for reuse into account—considering environmental, public health and economic regulations, and identifying key players involved in its operationalization. In some contexts, reuse has no legal status or existing environmental/public health standards may make reuse unattractive—for example, the cost to treat to the necessary standard would be greater than any possible revenue from the sale of the end product. The use of wastewater treatment by-products also requires specific organizational arrangements to ensure process operationalization; the utility responsible for the WWTP may not, however, be interested in, or able to be directly involved in, the resource recovery process. A project should therefore identify both the demand for by-products and the players who will be responsible for system management before wastewater treatment by-product recovery is considered. This is particularly true for small towns, which may be well positioned to connect with potential users of reuse by-products but may require support from regional or national agencies to help operationalize a reuse scheme.

Notes

1. *Sewage sludge* refers to the solids separated during the treatment of wastewater.
2. *Biosolids* refers to sewage sludge treated to a degree that meets pollutant and/or pathogen requirements for beneficial reuse.

Appropriate Wastewater Treatment Technology for Small Towns

3

Background to the "Appropriateness" of Technologies

Wastewater treatment is undertaken in a series of steps that can have increasing effectiveness and complexity, depending on the financial means and the human resources available to operate the systems. To guide the user through the identification of a wastewater project's physical, technical and financial boundaries, this section provides a list of criteria and a methodology that can help identify a subset of "appropriate" wastewater treatment technologies or process configurations for a specific project's particular context. Depending on the context, it may also be important to adopt an adaptive and incremental approach to wastewater treatment to better respond to the realities found in the small towns of low- and middle-income countries (LMICs) and to ensure that desired effluent quality levels and/or treatment objectives can be realistically met. This section will therefore focus on introducing wastewater treatment technologies that are deemed appropriate for small towns.

To support this guide, a series of two-page technology sheets has been developed. These provide an overview of the technology itself, the level of treatment that can be expected from each technology, selection criteria, and design considerations. The technology sheets, which are presented in Chapter 3, were developed with the considerations and criteria presented in this section in mind, and with the understanding of actual operating conditions of wastewater treatment plants (WWTPs) in small towns. Experience indeed shows that poor performance of treatment plants in LMICs, particularly for small towns, is often a result of a lack of operational expertise and of financial resources for adequate operation and maintenance (O&M), as well as whether the plant design included plans for O&M based on the available resources in the first place. That being said, it should be noted that the present document is not meant to serve as a design or an O&M manual, nor should the list of technologies presented hereafter be considered exhaustive. The aim of this section is to assist the user in intuitively making appropriate and informed decisions about technology selection by providing basic information that can be relevant for the design, financing, implementation, monitoring and O&M of cost-effective wastewater treatment systems in small towns. In addition, as wastewater treatment systems are composed of combinations of technologies in the primary, secondary and tertiary treatment steps, this section will also present appropriate wastewater treatment and sludge "treatment trains" for small towns.

Types of Wastewater Treatment Systems

Wastewater treatment systems can be *extensive* (or *natural*) and *intensive* (or primarily mechanically driven) systems. In extensive systems, such as anaerobic and facultative lagoons, treatment rates are typically relatively slow, requiring large retention times and land requirements to achieve acceptable treatment levels. Intensive systems, such as aerated lagoons, are based on higher reaction rates, resulting in more compact reactor volumes and a smaller treatment plant footprint, but at the cost of engineering complexity, and thus typically requiring continual operational support, regular routine maintenance, and a continuous, reliable external source of energy.

Extensive, or natural, treatment systems should be prioritized as much as possible for small towns as they are typically robust and are associated with low energy consumption. Where space is limited, however, alternative WWTP solutions are available along the broad extensive-intensive spectrum combining more technologically complex configurations that aim to increase treatment rates using a smaller layout footprint. Examples of these technologies include *upflow anaerobic sludge blanket* (UASB) reactors, *trickling filters* (TFs) or *anaerobic baffled reactors* (ABRs). These so-called *seminatural* systems are relatively robust and simple to operate but require more operational attention than natural systems, and they typically require additional steps to achieve a secondary level of treatment.

The technology sheets clarify the level of treatment that can be expected from each technology, except for the pretreatment technologies for which no specific sheets were created. Nevertheless, given their importance in enhancing the performance of downstream treatment processes, typical pretreatment unit operations are presented in the next section ("Levels of Wastewater Treatment"), along with other basic process considerations for small-town WWTPs.

Levels of Wastewater Treatment

Wastewater treatment plants are typically grouped into different levels of treatment, commonly referred to as *pretreatment*, *primary*, *secondary* and *tertiary* treatment. Additional treatment steps include advanced treatment and sludge treatment. These treatment levels group a variety of unit operations and processes of wastewater treatment, as presented in Table 3.1.

The technology sheets presented in this guide focus on *primary, secondary* and *tertiary* levels of wastewater treatment. No specific technology sheets are provided for *pretreatment* or for the *sludge treatment* stages; however, general guidance is provided on these treatment stages in this section. The sequence that treatment facilities typically use, consisting of primary, secondary and tertiary treatment stages, are known as *wastewater treatment trains*. Similarly, *sludge treatment trains* describe the multiple stages that are needed to treat the sludge generated from the wastewater treatment train. Appropriate wastewater treatment and sludge treatment trains are presented later in this chapter (see "The Optimum Combination of Technologies for Primary and Secondary Treatment" below).

Pretreatment Options and Process Considerations for Small Towns

As mentioned in Table 3.1, pretreatment (also referred to as *preliminary treatment*) is critical to protect downstream treatment process units and equipment from materials or substances that

TABLE 3.1
Levels of Wastewater Treatment

LEVEL OF TREATMENT	DESCRIPTION
***Pretreatment* (also referred to as preliminary treatment)**	The importance of pretreatment for small-town wastewater treatment solutions cannot be stressed enough. Pretreatment of wastewater protects the units and equipment further downstream in the treatment process from materials or substances that could hamper their performance or that could excessively increase the frequency or intensity of their maintenance needs. Pretreatment can help provide sustainable and cost-effective wastewater treatment solutions to small towns and, depending on the quality of the wastewater to be treated, several pretreatment processes could be required.
Primary	Primary treatment consists of the partial removal of suspended solids, organic matter and nutrients from wastewater. It produces a liquid effluent suitable for downstream secondary biological treatment and separates out solids as a sludge that should be treated before its ultimate disposal or reuse. Primary wastewater treatment is typically achieved by means of physical processes, such as sedimentation, but other types of treatment units can also be considered to provide a primary level of treatment, either on a stand-alone basis (septic/Imhoff tanks or digesters) or as the first step of a longer treatment chain (anaerobic ponds). Primary treatment can also help reduce fecal coliforms,[a] but secondary, and potentially tertiary, treatment will generally be required to make it fit for agricultural reuse.
Secondary	Secondary treatment aims at removing soluble and colloidal organic matter and suspended solids from wastewater, and it converts biodegradable organic matter into biomass, or sludge, through microbiological processes. Effective treatment can be achieved through aerobic processes, which require oxygen typically supplied by intensive mechanical aeration, facultative processes in which oxygen is supplied to bacteria through atmospheric reaeration and algal respiration in the water layer near the surface of lagoons, or anaerobic processes that harness anaerobic bacteria to convert organic matter into biogas. Secondary treatment can help further reduce fecal coliforms, but most options will still require tertiary treatment to produce effluent fit for agricultural reuse.
Tertiary	Tertiary treatment further improves the treatment level, beyond secondary treatment, of specific wastewater effluent parameters, such as nitrogen, phosphorus and suspended solids, as well as its hygienic quality (i.e., the removal of bacteria, viruses and other pathogens). The most common tertiary treatment process is a final disinfection stage, using ultraviolet radiation or chlorination. Other processes, such as polishing ponds, rock filters and other filter technologies, may also be used to meet specific effluent quality requirements. Such tertiary treatment effluent levels may, for instance, be required for agricultural reuse, groundwater recharge or discharge to recreational or protected waters. A small set of reuse options (for example, for potable reuse) would involve the use of additional steps, typically referred to as advanced treatment, including technologies such as reverse osmosis, ultrafiltration and microfiltration.
Sludge	All types of wastewater treatment plants produce sludge/biosolids as a by-product. In most small towns, sludge will require volume reduction before its disposal or reuse. Simple drying beds are typically a common solution, as they dewater the sludge and provide pathogen reduction. Additional treatment could be required to ensure further pathogen reduction before agricultural reuse.

[a] Fecal coliforms are bacterial organisms that are used to indicate the presence of fecal contamination.

could hamper their performance and/or their maintenance needs. Examples of wastewater contents or properties that could excessively increase maintenance needs include coarse materials, grit, oil and grease, as well as acute variations in wastewater concentrations and flow volumes. Protecting wastewater treatment systems in this way is particularly relevant to small-town contexts in terms of promoting sustainable and cost-effective wastewater treatment solutions in them. Table 3.2 presents typical pretreatment options and process considerations for small-town WWTPs.

TABLE 3.2
Typical Pretreatment Options and Process Considerations for Small-Town WWTPs

COMMON PRETREATMENT ISSUE	PRETREATMENT OPTION OR PROCESS CONSIDERATION	DETAILED DESCRIPTION
Coarse material (rocks, sticks, leaves, garbage and other debris) can damage pumps and other equipment and/or interfere with plant operability	Screening/sieving devices	Bar screens can be used to remove coarse material (rocks, sticks, leaves, garbage and other debris) from wastewater that would otherwise damage pumps and other equipment or interfere with plant operability. Depending on the downstream needs, there are various types of screening devices from coarse (100 to 25 mm) to medium (20 to 10 mm) to fine (10 to 3 mm), as defined by the gap separating the parallel screen bars, and there are manually and mechanically cleaned screens. Sieves feature further improved retention of solid matter because of small square or circular openings (mostly 1 to 5 mm in opening size), with their shape avoiding the passage of slim and longitudinal materials that can otherwise pass even fine screens. Sieves have, for instance, become common standard equipment upstream of UASBs to minimize scum formation in the latter. Rotating microscreens are special types of screens or sieves, in which the wastewater enters a slowly rotating drum, with the effluent passing through its cylindrical screen/sieve surface while solids are retained inside the drum. To avoid clogging, the retained matter is removed automatically by special cleaning and removal systems. In most cases, rotating microscreens have only small openings, ranging from about 0.1 to 3 mm, and the smaller the openings, the more the treatment efficiency of rotating microscreens resembles that of conventional primary settling tanks.
Grit with the potential to create clogging, damage equipment and reduce efficiency	Grit removal systems	Grit is the inert matter present in wastewater, which is heavier than the biodegradable organic solids to be degraded in the downstream treatment processes. If not removed, grit can clog downstream systems, reduce treatment efficiency by occupying valuable reactor volume, and cause abrasion damage and wear in equipment. Grit removal equipment should be located after screening devices and before primary treatment units. ■ **Horizontal flow grit chamber.** In small installations, grit can be removed by maintaining a low flow velocity in specific pretreatment channels or reactors, allowing grit to settle and lighter organic solids to be maintained in suspension and thus transported out of the channel. The settled grit can be manually or mechanically collected, though the former is typically favored in small plants. ■ **Vortex-type grit chamber.** These units make beneficial use of hydraulically induced vortex flow conditions. The grit spirals down along the perimeter of the cone- or cylinder-shaped reactor and is collected and removed at the bottom, and the degritted effluent is usually collected at the top. ■ **Aerated rectangular grit chamber.** Aerated rectangular grit chambers or aerated channels are typically used in larger works. In these installations, aerators diffuse coarse bubbles and produce a rolling motion, perpendicular to the wastewater flow. The heavier grit, washed free from organic matter by the turbulent flow, is collected at the bottom of the tank while lighter organic particles are suspended and eventually carried out. These systems also effectively allow for a preaeration of the wastewater and can be used to eliminate oil and grease within the same unit.

(continues on next page)

TABLE 3.2

Typical Pretreatment Options and Process Considerations for Small-Town WWTPs (*Continued*)

COMMON PRETREATMENT ISSUE	PRETREATMENT OPTION OR PROCESS CONSIDERATION	DETAILED DESCRIPTION
Varying levels of viscosity and density	Oil and grease removal	Oil and grease removal from wastewater involves separating substances or compounds that have a lighter density than water from the wastewater stream, and is commonly achieved through gravity separation, assisted flotation or chemical treatment. Whereas *oil* describes liquid products, such as vegetable oils, mineral oils and light hydrocarbons, the term *grease* refers to solid products or substances that originate from animal or vegetable sources and that may end up aggregating with suspended solids. Unit operations for oil and grease removal can also help collect other floating products, such as debris, soaps, foams, scum, detergents, plastics and so on.
Variable conditions, such as uneven concentrations or flow	Equalization	Wastewater treatment processes, particularly biological ones, work best with uniform conditions, and shocks in the form of sudden changes in the concentration of organic matter or of nutrients in the wastewater can lead to process upsets. Equalization can be done either to eliminate or dampen wastewater flow variations that may arise during the day (*flow equalization*) or to dampen concentration variations in wastewater (*concentration equalization*) that may be associated with heavy storms or industrial contributions, for example. In certain cases, it might be recommendable to include an equalization step in the treatment train in order to: ▪ Provide constant wastewater flows for the subsequent treatment steps and avoid feeding sudden concentration peaks to the biological steps of treatment processes. This can also help reduce the use of chemicals, as increased stability will require minimal dosage readjustments, thus minimizing wastage; ▪ Avoid by-passing the treatment plant during heavy storms; and ▪ Discharge an effluent of more constant quality into the receiving environment, thus reducing the risk of noncompliance with effluent standards.
Need to continually monitor/control flow in the system for improved stability of wastewater treatment	Flow measuring devices and flow distribution	All wastewater treatment plants require efficient flow measurement devices, at a minimum for both influent and effluent flows. Devices include Parshall flumes, venturi flow meters, electromagnetic or ultrasonic flow meters, and a variety of weirs in open channels. Weirs and flumes tend to be the most common devices as they offer a simple way to measure flow. Flow distribution devices, such as distribution boxes, flow splitters or tipping buckets, are a key element of treatment plants in that they allow the influent flow to be shared between two or more parallel treatment trains.
Wet weather flow exceeds wastewater treatment plant capacity	Stormwater detention basins	For combined stormwater and wastewater sewer networks, it is often necessary to add an additional treatment step to handle combined sewer overflow events. Stormwater detention basins refer to the combination of units that can help mitigate events when wet weather flows exceed the wastewater treatment plant capacity by diverting excess flows away from the treatment plant and providing a limited level of treatment (settling) before discharge into the environment—and/or after heavy rain events, the water stored in the stormwater basins can be progressively pumped back toward the wastewater treatment plant. This type of basin can also be part of a system for flow equalization.

Note: UASB = upflow anaerobic sludge blanket reactor; WWTP = wastewater treatment plant.

Preselection of Wastewater Treatment Technologies Appropriate for Small Towns

Although a wide array of wastewater technologies exists, not all of them are well suited for the requirements of small-town WWTPs. Therefore, to narrow down the technology options included in this guide as likely to be most appropriate to small towns, twenty-one have been shortlisted using preselection criteria and these preselected technologies are the focus of this guide.

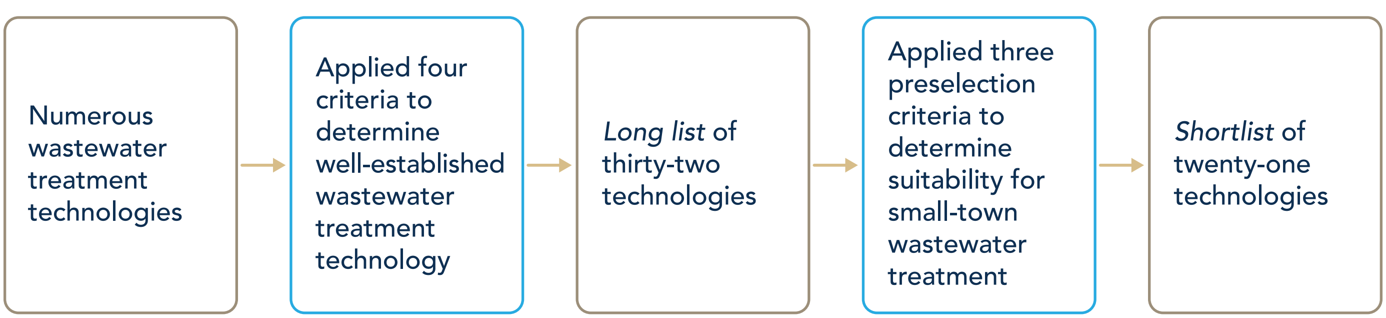
This *shortlist* was developed in two stages:

- First, a *long list* of technologies was established.
- Then, the *long list* was subjected to preselection criteria, which led to the exclusion of certain technologies from further consideration if deemed unsuitable to small-town wastewater treatment. **Only the remaining technologies are further developed as part of this guide**.

For the establishment of the *long list* of wastewater treatment technologies, the following inclusion criteria were used:

(a) **Only well-established WWTP technologies are included.** These are technologies that have been applied frequently in large-scale projects and for which generally acknowledged design rules exist. Nevertheless, the long list does not include technologies for which only few large-scale references exist or for which design rules are still under discussion within the engineering and academic communities. For this reason, technologies such as *evaporative systems* or *epuvalisation* were not included in the long list.

(b) **Default to the most recent variation of an established technology.** Some technologies have been improved and upgraded into variations, which are now widely considered to be safer and more cost-effective and show improved performance and general process robustness. In such cases, the improved version of the technology was included and not the older precursor technologies. For instance, the *infiltration-percolation* technology (also called *intermittent sand filters* [ISFs]) is now being abandoned for new construction projects globally in favor of *constructed wetlands* (CWs), which are de facto sand filters complemented by vegetation. These have proved to be even more efficient in terms of organic, solids, nutrients and pathogen removal, with improved stability against hydraulic peak loads and with considerably less risk of clogging compared with ISFs.



(c) **New technologies that are proving to be efficient and that are gaining prominence.** The guide includes various new developments that have recently become increasingly popular, such as *hybrid CWs*, and combinations of secondary treatment components, such as *UASB-waste stabilization ponds (WSPs)* and *UASB-trickling filters (TFs)*. Such combinations can prove quite advantageous when compared to non-combined single process units because such combinations usually reduce costs and simultaneously increase treatment efficiencies.

(d) **Not all variations or modifications of a technology are appropriate or relevant.** It is common practice in wastewater treatment to use simple terms to describe complex technologies, such as *activated sludge*, *trickling filter, anaerobic treatment*, and so on. However, such simplifications can mask a wide range of quite different technological variations, not all of which may be appropriate for specific projects—in this case, for small towns. This is particularly true for activated sludge and its *extended aeration* (EA) or *low-load* modifications. This applies to both batch-wise variations, such as *sequencing batch reactors* (SBRs), and flow-through type facilities, such as *oxidation ditches* (ODs). A comparative description and analysis of *conventional activated sludge* (CAS) and EA is presented in Appendix A.

The resulting *long list* of well-established technologies is presented in Table 3.3. This *long list* was further narrowed down using the three following specific criteria in order to identify a *short list* of appropriate WWTP options for small towns:

(a) **The technology design capacity should be appropriate for small town sizes.** Small towns are defined in Chapter 2 as having a population of mostly less than 50,000 people, sometimes less than 100,000 people and, very rarely, even more than 100,000 people. In addition, the expected per capita wastewater pollution level in LMICs and transition countries, where this guide is intended to be applied, is most likely to be less than 60 g BOD_5/cap/d (for example, in the range of 30 to 50 g BOD_5/cap/d). An appropriate design capacity of such WWTPs should typically be < 50,000 PE60 (roughly equivalent to < 5 MLD), with a maximum of < 100,000 PE60 (< 10 MLD) in rare cases. Therefore, WWTP design sizes appropriate for small towns are < 50,000 PE60 and < 5 MLD (with rare maxima of up to 100,000 PE60 and < 10 MLD).[1]

(b) **Technologies should be simple to operate and present low operational risks.** Finding sufficient personnel to operate and maintain WWTPs in small towns can present a challenge, so the technologies chosen should be simple to operate with low operational risks.

(c) **Capital expenditures (CAPEX) and operating expenditures (OPEX) associated with technologies should be affordable.** Financial aspects play a crucial role in the sustainable running of small-town WWTPs, so CAPEX and OPEX should be kept within the service provider's financial capacity. This is particularly important to consider for electromechanical installations, as these tend to get over-proportionally expensive to purchase, operate and maintain as they get smaller. Technologies such as *chemically enhanced primary treatment* (CEPT), *flotation* or *thermal sludge dryers* were therefore not considered as part of the

TABLE 3.3

Long List of Treatment Technologies and Preselection of Appropriate Technologies for Small-Town WWTPs

#	WASTEWATER TECHNOLOGY[a]	ABBREV.	APPLIED FOR WWTP DESIGN SIZES < 50,000 PE60 AND < 5 MLD	SIMPLE TO OPERATE WITH LOW OPERATIONAL RISKS	FINANCIALLY COMPETITIVE FOR SMALL/ MEDIUM WWTPS[b]
Primary treatment (only)					
1	Septic tank	ST	(only for clusters of houses)	Yes	Yes
2	Biogas digester	BD		Yes	Yes
3	Imhoff tank	IMH	Yes	Yes	Yes
Primary + secondary treatment					
4	Anaerobic baffled reactor	ABR	Yes	Yes	Yes
5	Anaerobic filter	ANF	Yes	Yes	Yes
6	Waste stabilization pond	WSP	Yes	Yes	Yes
7	Aerated lagoon	AL	Yes	Yes	Yes
8	Single-stage constructed wetland	CW(1-st)	Yes	Yes	Yes
9	Hybrid constructed wetland	CW(hybrid)	Yes	Yes	Yes
10	Upflow anaerobic sludge blanket reactor	UASB	Yes	Yes	Yes
11	Conventional activated sludge process	CAS	(> 20,000 PE60)	No	No
12	Sequencing batch reactor (conventional)	SBR (conv.)	(> 20,000 PE60)	No	No
13	Extended aeration (AS type)	EA	Yes	Yes	Yes
14	Extended aeration (SBR type)	SBR EA	Yes	Yes	Yes
15	Trickling filter	TF	Yes	Yes	Yes
16	Rotating biological contactor	RBC	Yes	Yes	Yes
Activated sludge variations					
17	Nereda®[c]	NEREDA	Yes	No	No
18	Membrane bioreactor	MBR	Yes	No	No
19	Two-stage AS with high-loaded first stage	AB	No	No	No
Attached biomass growth system variations					
20	Biological aerated filter[d]	BAF	Yes	No	No
Combinations of AS and attached growth					
21	Integrated fixed film activated sludge[e]	IFAS	Yes	No	Yes
22	Moving bed biological reactor[f]	MBBR	Yes	No	Yes
23	Trickling filter/solids contact process	TF/SC	No	Yes	Yes
24	UASB-WSP	UASB-WSP	Yes	Yes	Yes
25	UASB-TF	UASB-TF	Yes	Yes	Yes
26	UASB-AS	UASB-AS	Yes	No	Yes
Tertiary treatment (additional)					
27	Disinfection with UV system	UV	Yes	Yes	Yes
28	Disinfection with chlorine	Cl	Yes	Yes	Yes
29	Polishing pond	PP	Yes	Yes	Yes
30	Rock filter	RF	Yes	Yes	Yes
31	Sand filter	SF	Yes	No	No
32	Rotary disc filter	RDF	Yes	Yes	Yes

Note: AS = activated sludge; CAPEX = capital expenditures; MLD = million liters per day; OPEX = operating expenditures; PE = population equivalent; UV = ultraviolet; WWTP = wastewater treatment plant.

[a] Appropriate WWTP technologies are presented in green text.

[b] Technologies that have considerably higher CAPEX and/or OPEX figures than other technologies are not considered to be financially competitive.

[c] Nereda is a proprietary variation of AS based on aerobic granulation.

[d] These systems can come under different proprietary variations and trademarks such as BIOFOR® and BIOSTYR®.

[e] These systems can come under different proprietary variations and trademarks such as STM-Aerotor™.

[f] These systems can come under different proprietary variations and trademarks such as Kaldnes™, Linpor™ and Captor™.

long list of this guide. Economies of scale effects also exist for *civil works-intensive* technologies, but this effect is usually less pronounced than for electromechanical installations.

Technologies were excluded for being inappropriate for small towns if they did not meet all three of the aforementioned criteria. For example, the CAS process (*high-load*) or *membrane bioreactors* (MBRs) were not considered part of the guide because they are widely known to require a combination of higher levels of CAPEX and OPEX, highly skilled staff, a constant electricity supply, high levels of chemical consumption and a highly developed management system that ensures that the facility is correctly operated and maintained. In addition, given the economies of scale and the reduced fluctuation of influent characteristics in larger towns and cities, these options are deemed more appropriate for the treatment of large flows in such settings.

In Table 3.3, wastewater treatment technologies that meet all of the preselection criteria, and are therefore deemed appropriate for small towns, are presented in green text, and those excluded technologies, based on the fact that they do not meet the preselection criteria for small towns, are presented in red text.

Twenty-one options met the preselection criteria of being appropriate for small towns, as presented in Table 3.4. More experienced users of this guide may still wish to include other technologies for additional comparison. However, we suggest that any additions be assessed against the same criteria that are applied in this guide for comparability with the preselected technologies here.

For those technologies that met the preselection criteria, technology sheets were developed. These are presented in the next section ("Technology Sheets").

TABLE 3.4
List of Wastewater Treatment Technologies That Met the Preselection Criteria of Being Appropriate for Small Towns

#	TECHNOLOGY SHEET: APPROPRIATE TECHNOLOGY FOR SMALL TOWNS
	Primary treatment only
1	Septic tank (ST)
2	Biogas digester (BD)
3	Imhoff tank (IMH)
	Primary and secondary treatment
4	Anaerobic baffled reactor (ABR)
5	Anaerobic filter (ANF)
6	Waste stabilization pond (WSP)
7	Aerated lagoon (AL)
8	Single-stage constructed wetland (CW(1-st))
9	Hybrid constructed wetland (CW(hybrid))
10	Upflow anaerobic sludge blanket reactor (UASB)
11	Extended aeration – activated sludge type (EA)
12	Extended aeration – sequencing batch reactor type (SBR(EA))
13	Trickling filter (TF)
14	Rotating biological contactor (RBC)
15	UASB followed by WSP (UASB-WSP)
16	UASB followed by TF (UASB-TF)
	Tertiary treatment
17	Disinfection with ultraviolet system (UV)
18	Disinfection with chlorine (Cl)
19	Polishing pond (PP)
20	Rock filter (RF)
21	Rotary disc filter (RDF)

Technology Sheets

To help better navigate the reader around the technology sheets, we present here an outline template that provides an overview of how each technology sheet is structured and an explanation of how to interpret the different figures that are used to characterize each technology.

TECH SHEET #1

Septic Tank (ST)

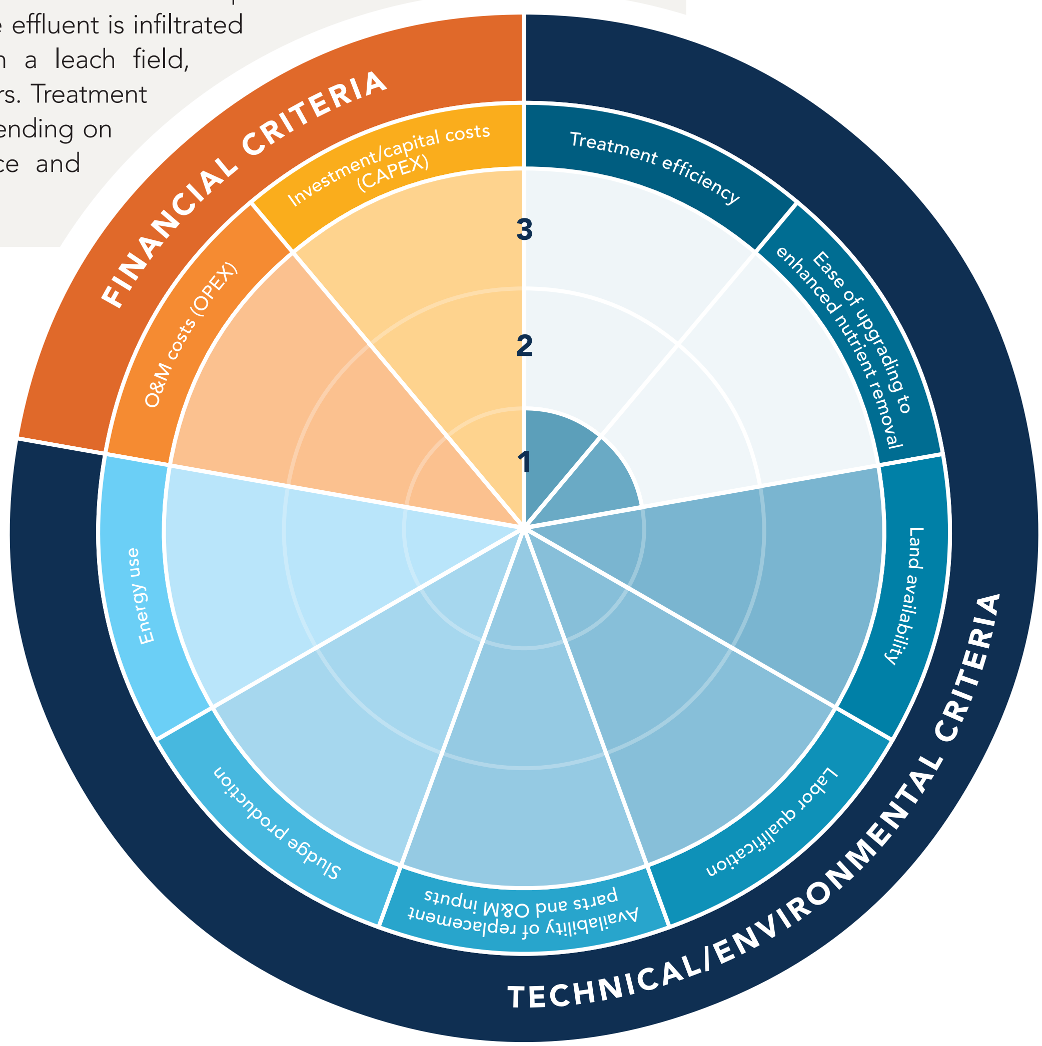
DESCRIPTION

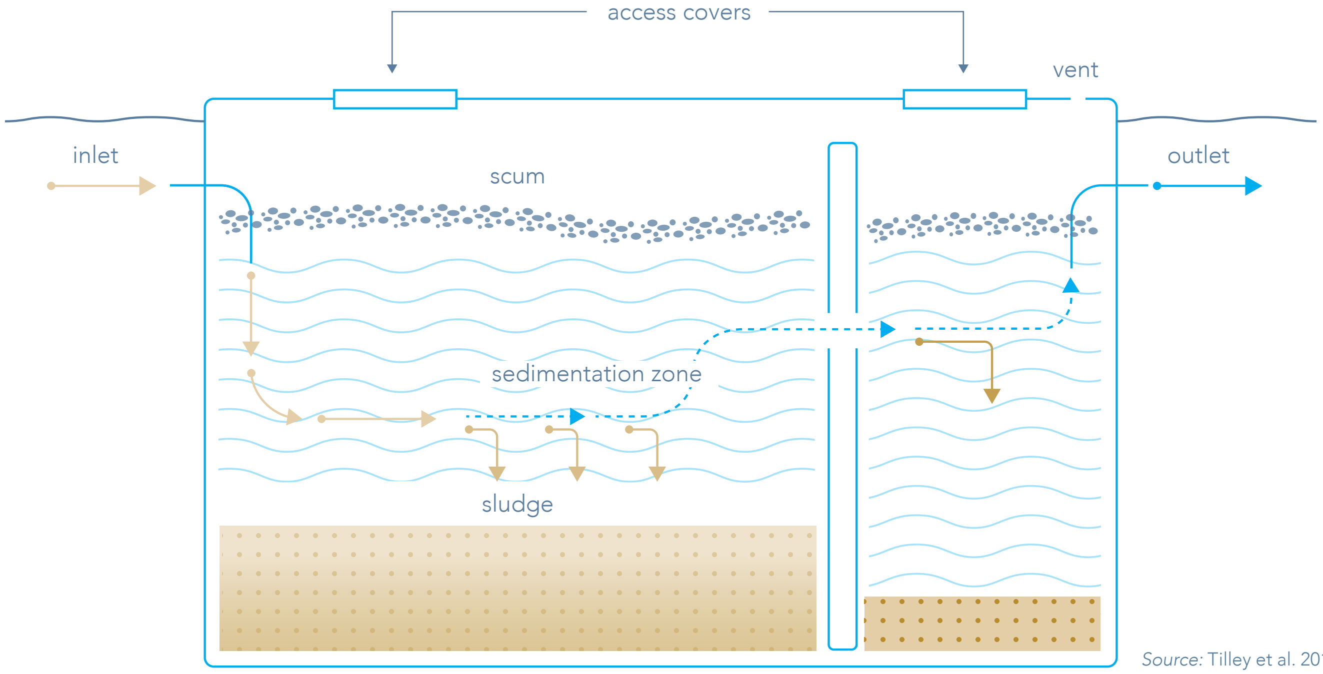
Primary anaerobic treatment

The septic tank is the most common, small-scale and decentralized treatment technology worldwide. The septic tank is a watertight chamber that performs preliminary treatment through sedimentation and anaerobic digestion. Physical treatment happens through the retention of solids: the gravity separation of solid particles between flotation (formation of a grease cap) and sedimentation (formation of a sludge bed) produces a totally liquid effluent. Biological treatment occurs through anaerobic digestion which liquefies solids retained in the pit and produces some biogas. The effluent is infiltrated onsite and spread through a leach field, where further filtration occurs. Treatment efficiencies vary greatly depending on operation and maintenance and climatic conditions.

REUSE POTENTIAL

- Effluent not fit for reuse.
- Not enough biogas produced for reuse.





Source: Tilley et al. 2014.

PROJECT

- **Connected population:**
  (Household) or
  (Cluster of houses)
- Population growth can be accounted for as the sizing is relatively flexible to a maximum of 200 population equivalent.
- Consider existing capacity for sludge treatment in neighboring areas. Mixed wastewater flow is not allowed.

DESIGN

- Simple and robust technology with long service life; can be sized and constructed by non-expert.
- Small land area required (can be built underground).
- Treated wastewater can be dispersed into the soil for onsite infiltration.
- If septic tanks are used in densely populated areas, onsite infiltration should not be used, otherwise, the ground will become oversaturated and contaminated, and wastewater may rise up to the surface, posing a serious health risk.
- Even though septic tanks are watertight, it is not recommended to construct them in areas with high groundwater tables or where there is frequent flooding.

OPERATION

- Regular desludging must be ensured.
- A septic tank is appropriate where there is a way of dispersing or transporting the effluent.

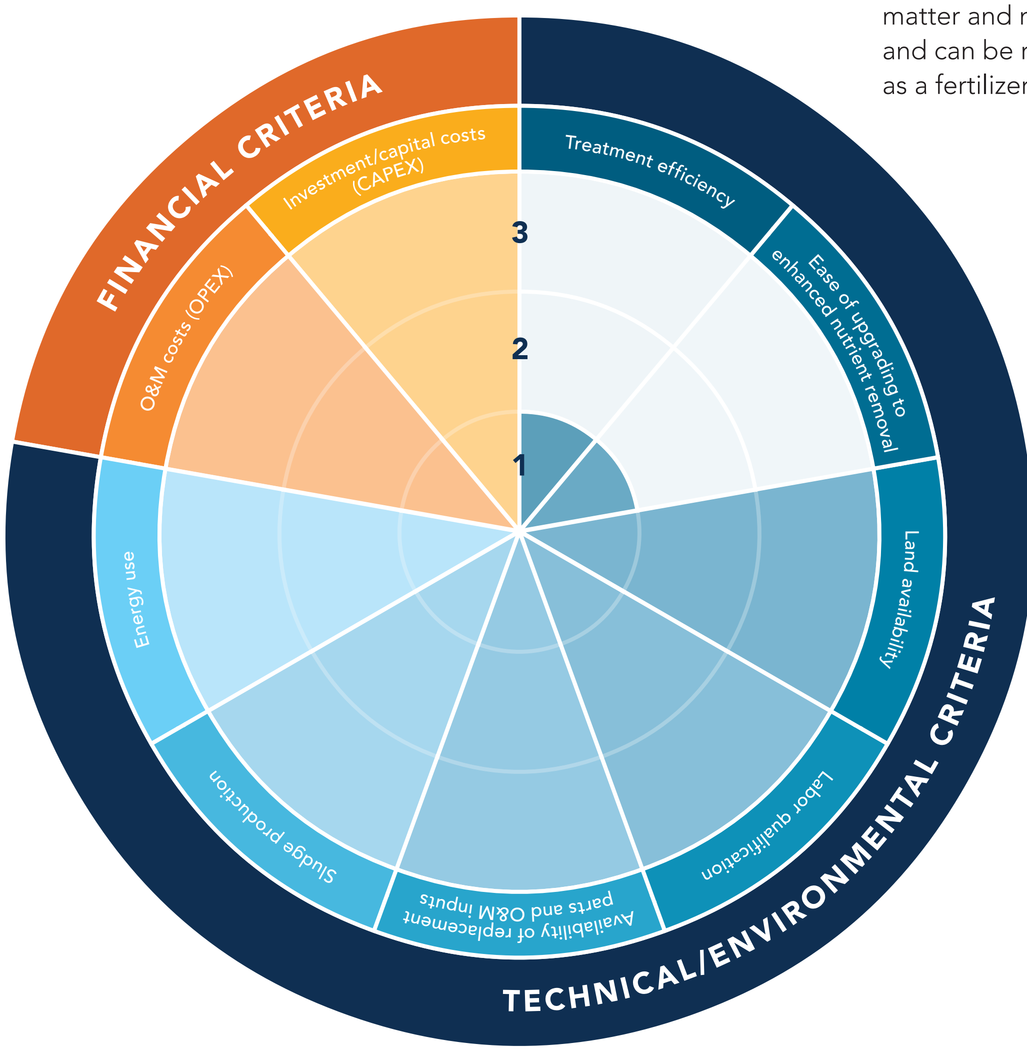
TECH SHEET #2
Biogas Digester (BD)

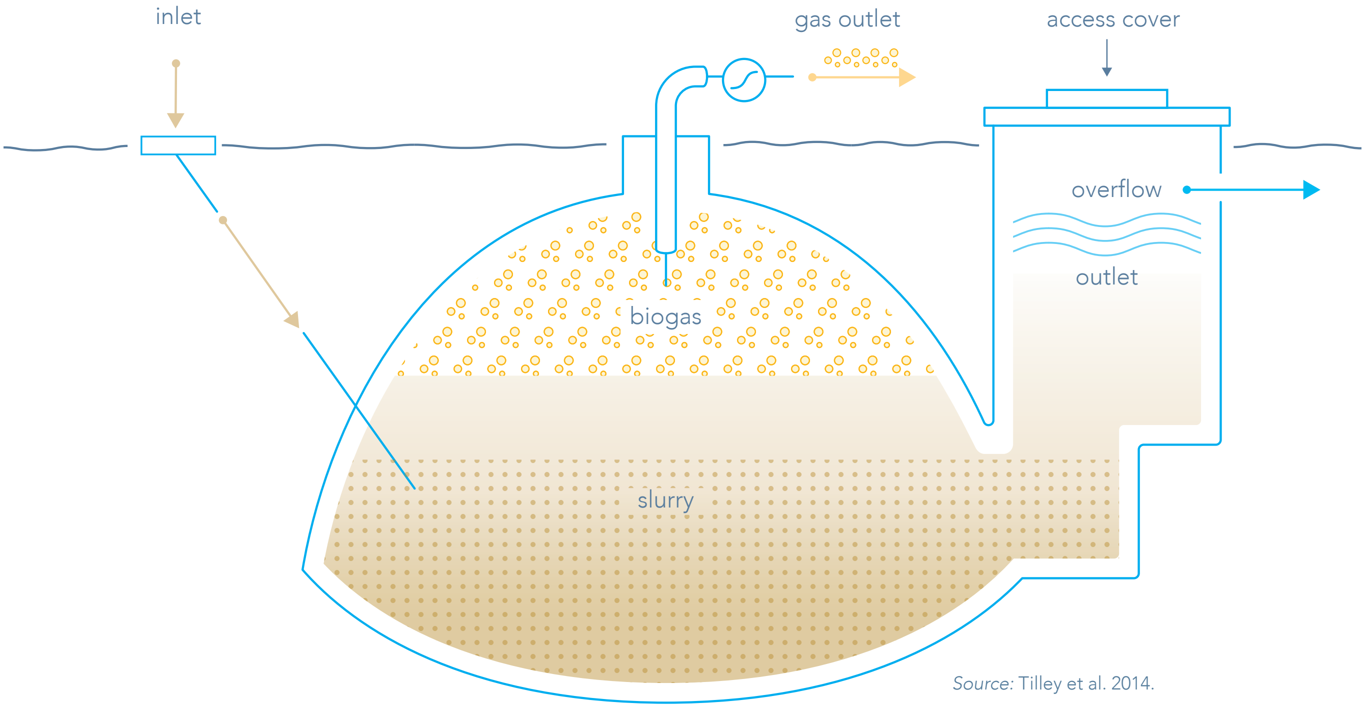
DESCRIPTION

Primary treatment, anaerobic process, sludge treatment
The biogas digester consists in a chamber where blackwater, sludge, and/or biodegradable waste is introduced with no aeration to create the ideal conditions for anaerobic bacteria to break down (digest) the organic matter from the inputs into simpler chemicals components. Anaerobic digestion is a process which take place in low oxygen or anoxic environments. In these conditions, anaerobic bacteria thrive and break down organic carbon into biogas (methane and carbon dioxide) and produces a digested slurry (digestate) rich in organics and nutrients, almost odorless and where pathogens are partly inactivated. Because this digester is used for strong substrate only, biogas production is high; however, significant gas production cannot be achieved if blackwater is the only input. This process can be very useful to treat arising organic waste such as sewage sludge, organic farm waste, municipal solid waste, green waste and industrial organic waste.

REUSE POTENTIAL

- Effluent not fit for reuse.
- Market for reuse exist for biogas and sludge (digestate) valorization.
- Gas production is directly related to the organic fraction of the substrate.
- Digestate is rich in stabilized organic matter and nutrients and can be reused as a fertilizer.





Source: Tilley et al. 2014.

PROJECT

- **Connected population:** (Household) or (Cluster of houses)
- **Power and water supply:** Does not require electricity or constant water supply. Will not accommodate only wastewater and therefore benefits from nearby agricultural or industrial activity to supplement inputs with animal manure, green waste or organic waste, or a food waste collection system.
- Mixed wastewater and organic waste is allowed. However, the influent should remain strong and the system will not deal well with dilution.

DESIGN

- Often, biogas reactors are directly connected to private or public toilets with an additional access point for organic materials.
- For economic reasons, it is not suitable for weak liquid wastewater, as the total volume of wastewater must be agitated and kept for full retention time inside the digester. This leads to large digester volumes and thus, to high construction costs.
- Can be built underground if soil conditions and initial space allows.
- Construction requires masonry knowledge.
- To minimize distribution losses, the reactors should be installed close to where the gas can be used.

OPERATION

- The main parameter is the hydraulic retention time, which should not be less than 15 and 25 days in hot and moderately warm climate, respectively. Below 15 °C biogas digesters are less appropriate for colder climates as the rate of organic matter conversion into biogas is very low.

TECH SHEET #3

IMHOFF Tank (IMH)

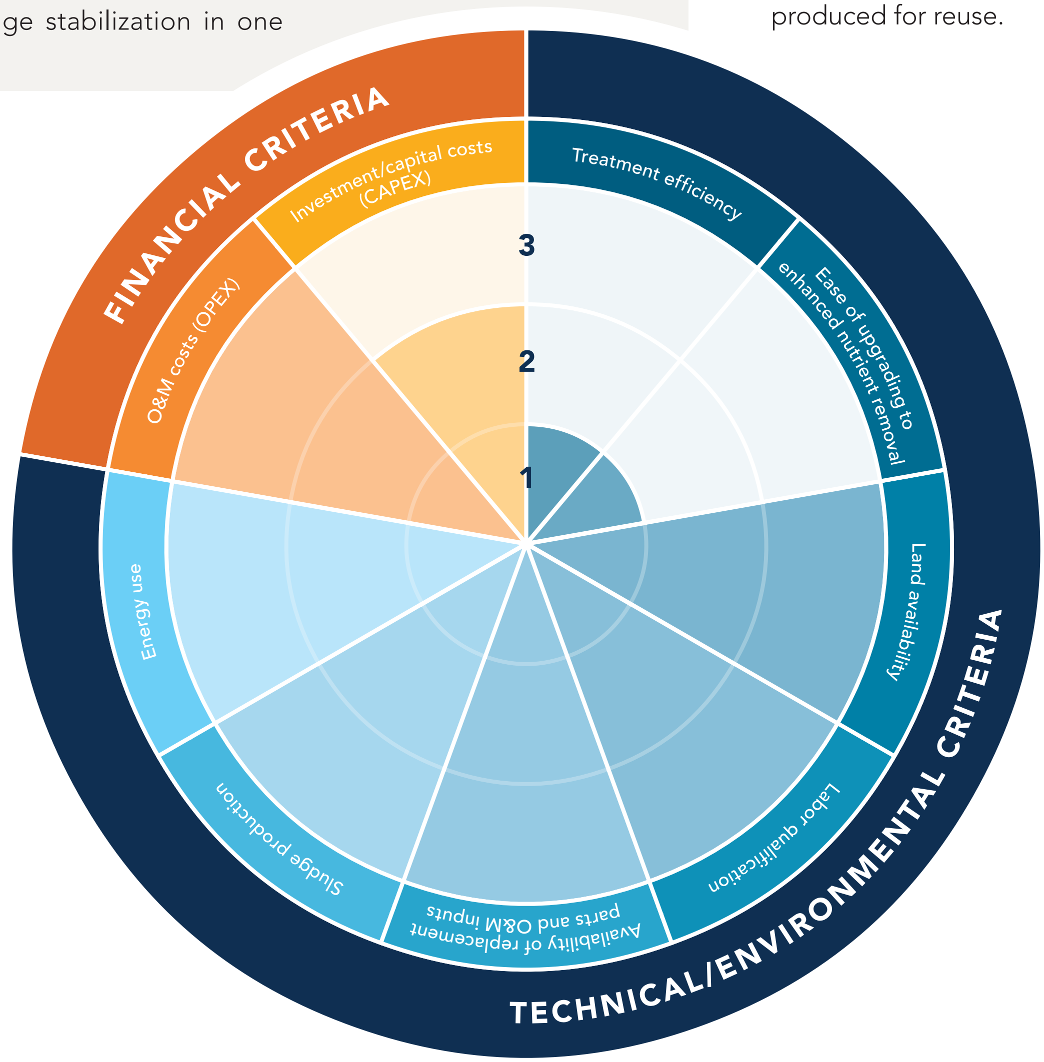
DESCRIPTION

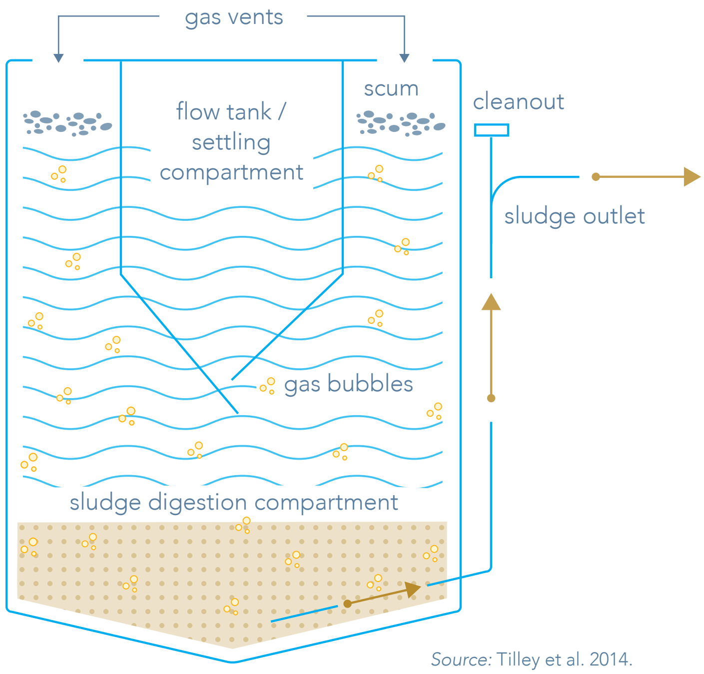
Primary anaerobic technology

The Imhoff tank is a communal settling tank that treats raw wastewater by separating solids and liquids. The settled solids are then digested and partially stabilized in the lower chamber through anaerobic digestion. The V shape allows solids to trickle into the digestion compartment while preventing gas from rising back up and disturbing the settling process. Gas vents direct the gas to the sides, transporting sludge particles and creating a scum layer. Imhoff tanks work for domestic or mixed wastewater flows, though the effluent requires additional treatment. The combination of solid-liquid separation and sludge stabilization in one unit is advantageous.

REUSE POTENTIAL

- Effluent not fit for reuse.
- Treated wastewater can be discharged in ocean or large river only.
- Not enough biogas produced for reuse.





Source: Tilley et al. 2014.

PROJECT

- **Connected population:**
  (Cluster of houses) or
  (Town)
- Consider existing capacity for sludge treatment in neighboring areas.
- Mixed wastewater flow is allowed. Resistant against organic shock loads, but not suitable for hydraulic overloads.

DESIGN

- Due to depth of tank, the height of the groundwater table should be considered carefully.
- Moderate area requirement (can be built underground).

OPERATION

- Process operation in general is not required, and maintenance is limited to the removal of accumulated sludge and scum every 1 to 3 years.
- Low odors due to containment of gas.
- Performance depends on temperature. In colder climates, a larger tank may be needed for longer retention.
- Usually, the biogas produced in an Imhoff tank through anaerobic digestion is not collected because of its insufficient amount.

Anaerobic Baffled Reactor (ABR)

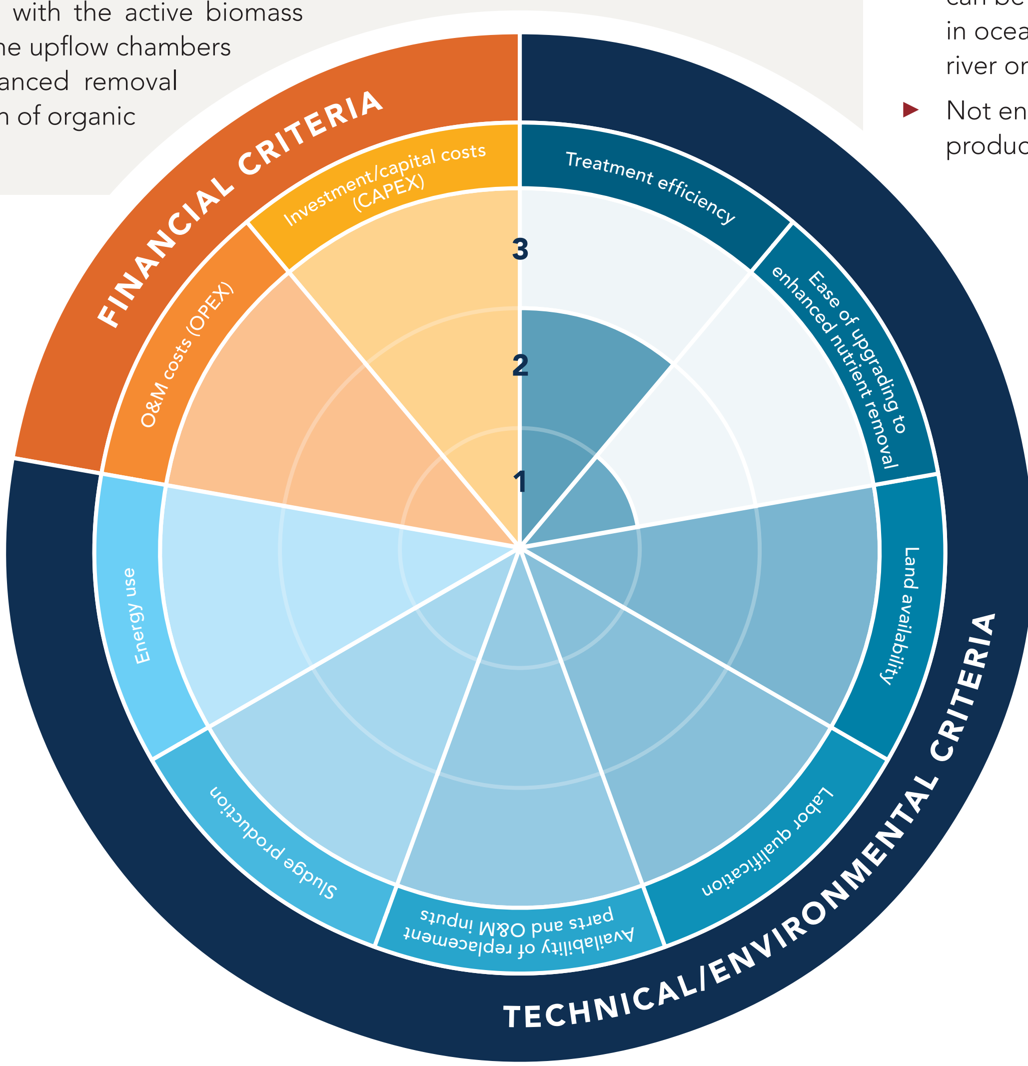
DESCRIPTION

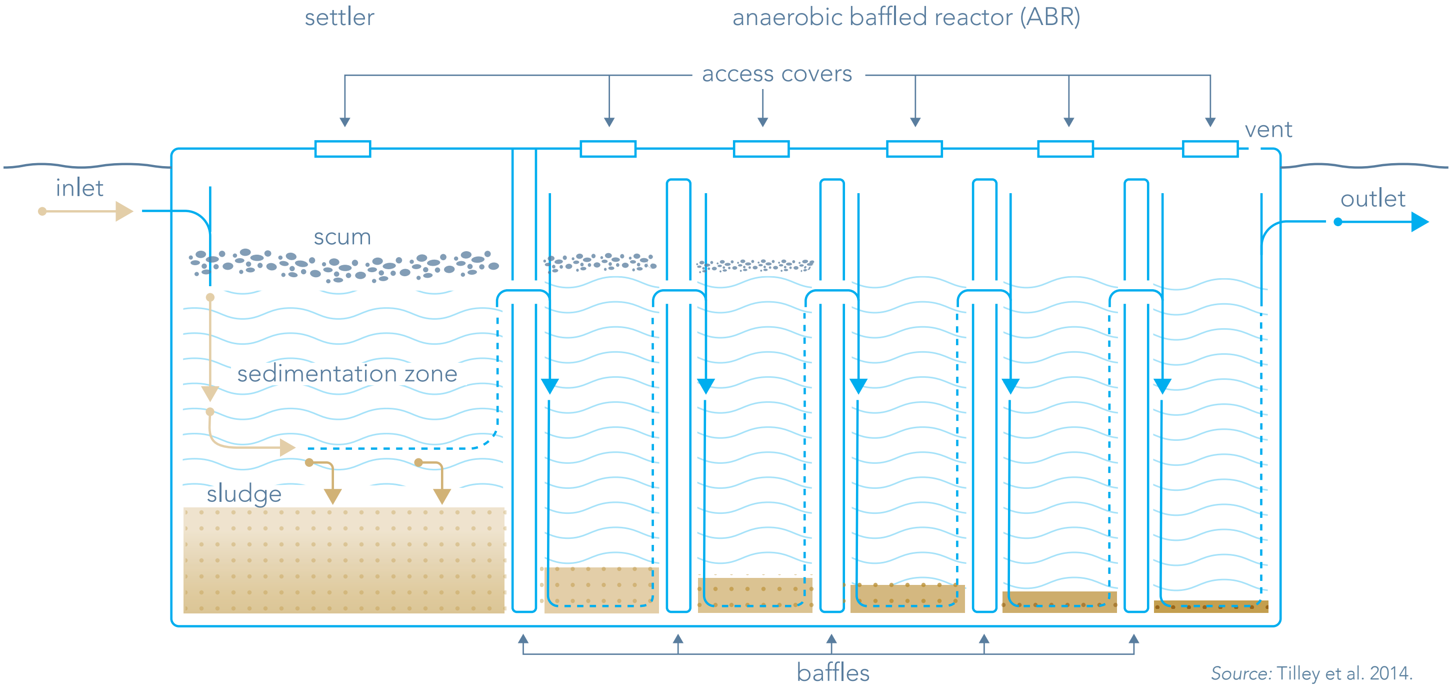
Primary anaerobic treatment

An anaerobic baffled reactor (ABR) is an improved Septic Tank with a series of baffles under which the wastewater is forced to flow through several compartments. The ABR also treats of non-settleable and dissolved solids by bringing them in close contact with active bacterial mass that accumulates on the reactor walls. The increased contact time with the active biomass results and the upflow chambers provide enhanced removal and digestion of organic matter.

REUSE POTENTIAL

- Effluent not fit for reuse.
- Treated wastewater can be discharged in ocean or large river only.
- Not enough biogas produced for reuse.





Source: Tilley et al. 2014.

PROJECT

- **Connected population:** (Cluster of houses) or (Town)
- Consider existing capacity for sludge treatment in neighboring areas.
- Mixed wastewater flow is allowed. Resistant to organic and hydraulic shock loads.

DESIGN

- Moderate area requirement (can be built underground).

OPERATION

- Process operation in general is not required, and maintenance is limited to the removal of accumulated sludge and scum every 1 to 3 years.
- Low sludge production; the sludge is stabilized.

TECH SHEET #5

Anaerobic Filter (ANF)

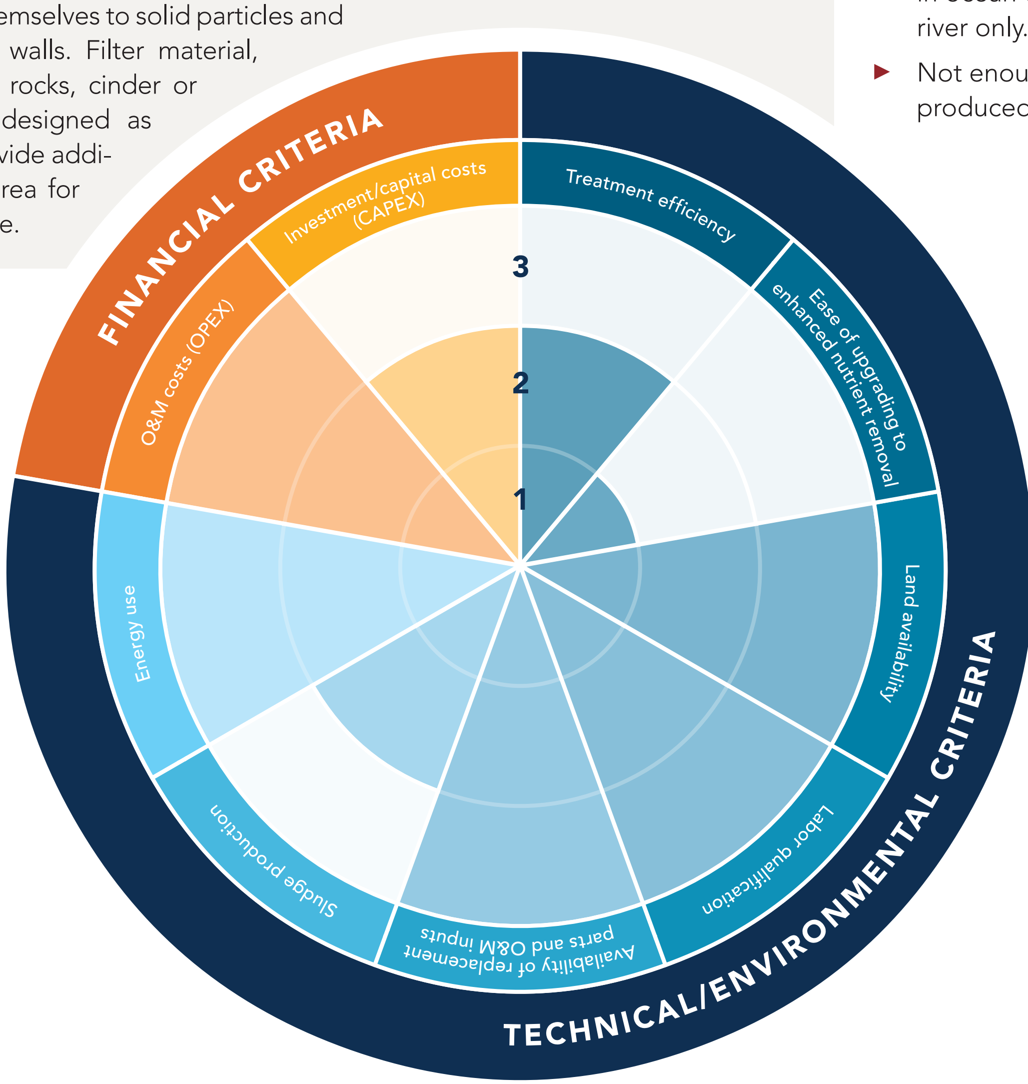
DESCRIPTION

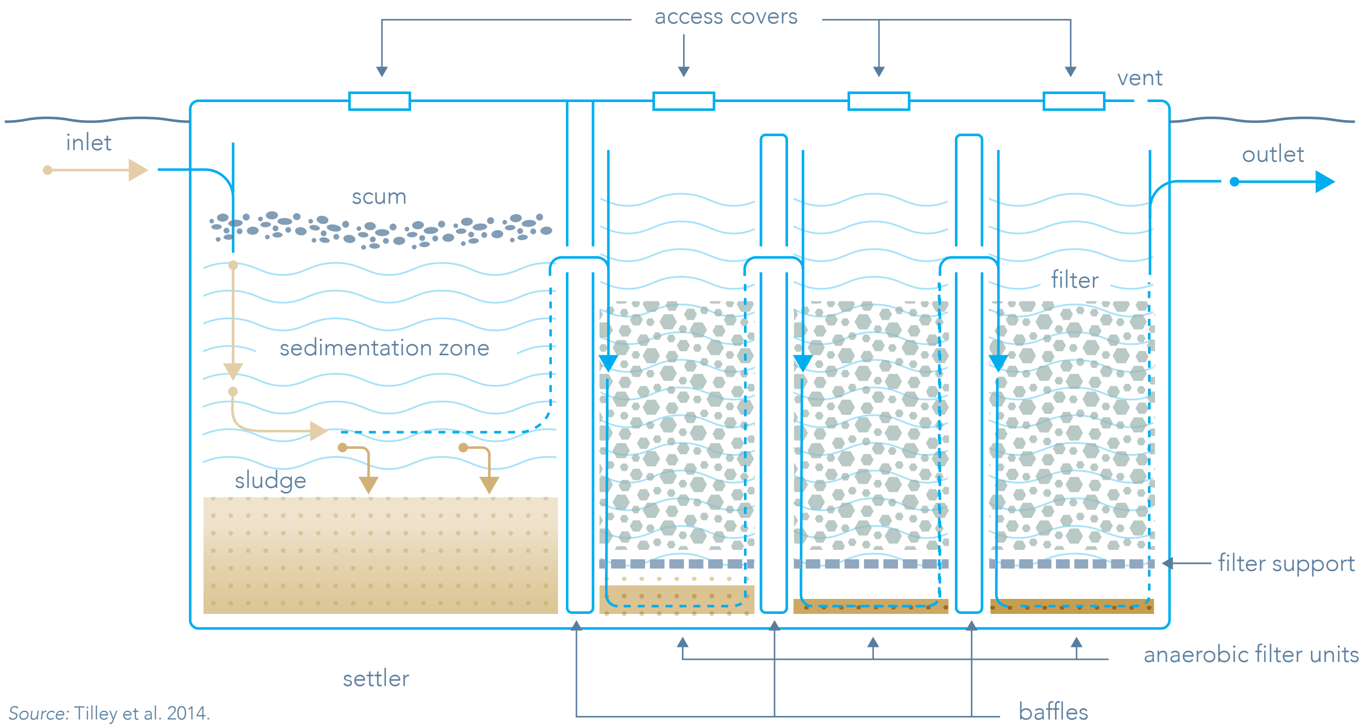
Primary anaerobic treatment

The anaerobic filter, also known as fixed bed or fixed film reactor, consists in an anaerobic baffle reactor structure equipped with additional material that forms a filter on which bacteria can grow. This increases the surface area where wastewater is in contact with active biomass and improves treatment. The treatment of non-settleable and dissolved solids occurs through contact with this surplus of active bacterial mass. The bacteria affix themselves to solid particles and on the reactor walls. Filter material, such as gravel, rocks, cinder or plastic pieces designed as such media provide additional surface area for bacteria to settle.

REUSE POTENTIAL

- Effluent not fit for reuse.
- Treated wastewater can be discharged in ocean or large river only.
- Not enough biogas produced for reuse.





Source: Tilley et al. 2014.

PROJECT

- **Connected population:** (Cluster of houses) or (Town)
- Consider existing capacity for sludge treatment in neighboring areas.
- Mixed wastewater flow is allowed.

DESIGN

- Hydraulic retention time is the most important design parameter influencing filter performance. The hydraulic retention time should be in the range between 1.5 and 2 days.
- For domestic wastewater, constructed gross digester volume (voids plus filter mass) may be estimated at 0.5 m3/ capita.
- Moderate area requirement (can be built underground).

OPERATION

- Risk of clogging, depending on pre-treatment.

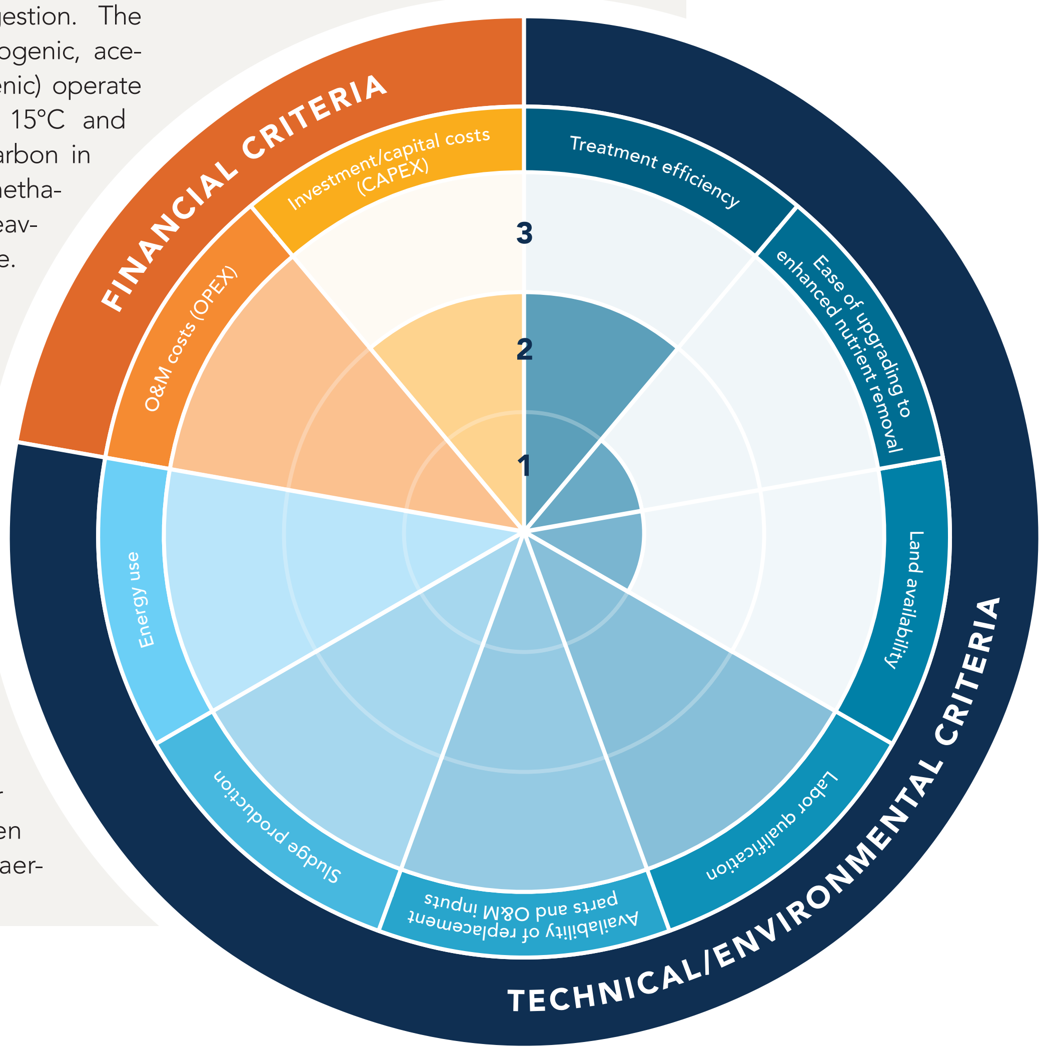
TECH SHEET #6

Waste Stabilization Ponds (WSP)

DESCRIPTION

Primary/secondary/tertiary anaerobic treatment
Secondary/tertiary aerobic treatment
Waste Stabilization Ponds are man-made ponds and can be used at all stages of wastewater treatment, in series or as one step in a broader treatment chain.

- **As primary anaerobic treatment,** anaerobic lagoons or ponds operate much like open septic tanks and are used as the first step to treat strong wastewater and reduce organic load. The depth of anaerobic ponds promotes sedimentation: settleable solids fall to the bottom of the pond to form a sludge layer, where they undergo anaerobic digestion. The anaerobic bacteria (acidogenic, acetogenic, and methanogenic) operate at temperatures above 15°C and transform the organic carbon in the solids into biogas (methaneand carbon dioxide), leaving a nutrient-rich sludge. The scum layer that often forms on the surface does not need to be removed. Anaerobic ponds are particularly well adapted for warm countries.
- **As secondary treatment,** facultative ponds rely on both aerobic and anaerobic processes. Facultative ponds stratify influent by working on two levels: the top layer contains dissolved oxygen due to atmospheric reaeration and algal respiration, while the sludge settles at the bottom and provides an anaerobic environment where decomposition occurs and the sludge has to be regularly extracted. Usually, a facultative pond receives settled water from an anaerobic pond and therefore operates

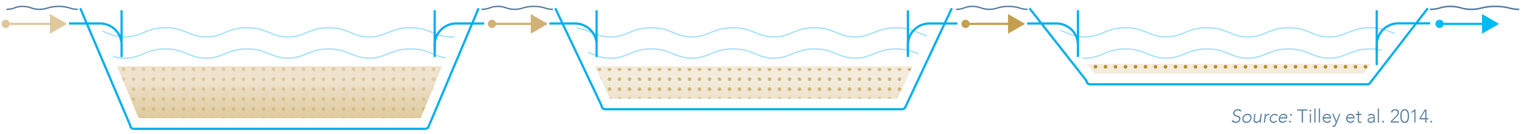


under lighter organic loading than anaerobic ponds. Wastewater flows into the pond in a continuous manner. Facultative ponds are used to treat raw municipal wastewater in small communities and for primary or secondary effluent treatment for small or large cities.

- **As tertiary treatment,** aerobic or maturation ponds rely on natural aeration, sedimentation and UV disinfection to treat wastewater. This process mirrors the natural treatment occurring in a river body. Natural oxygenation occurs through atmospheric reaeration and algal respiration, promoting organic degradation and nutrient removal. Wastewater flows in continuously, and the shallow depth of the pond allows sunlight to reach the whole pond depth, combining with the oxygen to promote pathogen removal. All these processes contribute to good fecal bacterial removal. Photosynthetic algae release oxygen in the water while consuming the carbon dioxide produced by bacterial activity. They are also used as the polishing step after an anaerobic system, such as USABs (see sheet 10). Maturation ponds contribute significantly to pathogen removal and effectively remove the majority of nitrogen and phosphorus if used in combination with algae harvesting. The algal population in maturation ponds is much more diverse than in the facultative ponds.

REUSE POTENTIAL

- If the anaerobic pond is covered, the biogas can be recovered for reuse.
- Maturation lagoon effluent is fit for non-restrictive irrigation.
- Due to high algae production, use through drip irrigation requires filtration to remove the suspended solids.



Source: Tilley et al. 2014.

PROJECT

- **Connected population:**
  (Cluster of houses) or
  (Town)
- Can accommodate high organic loading.
- Mixed wastewater flow is allowed. Population growth can be accounted for as the sizing is relatively flexible.

DESIGN

- Works best in series.
- Requires relatively large areas of land, and therefore is still best suited for peri-urban areas or large, rural settlements.
- Anaerobic lagoons are usually 2 to 5 m deep and the height of the groundwater table should be considered carefully.
- Facultative ponds usually are 1.5 m deep, although depths between 1 m and 2.0 m are used. Depths less than 0.9 m are not recommended, as rooted plants may grow in the pond and provide a shaded habitat suitable for mosquito breeding.
- Maturation ponds are usually 1–1.5 m deep.
- Anaerobic lagoons receive raw wastewater with high organic loading (>100g BOD_5/m^3 per day).
- Aerobic lagoons can be built in series for most effective treatment and to provide a high level of pathogen removal.
- Although fecal bacteria are partially removed in the facultative ponds, the size and number of the maturation ponds determine the quantity of fecal bacteria in the final effluent.

OPERATION

- Odor release (mainly hydrogen sulfide) is a major disadvantage of anaerobic ponds.
- Anaerobic treatment requires a longer start-up time, alkaline addition and anaerobic microbes are sensitive to toxic substances.
- Anaerobic lagoons must be de-sludged approximately once every 2 to 5 years, when the accumulated solids reach one third of the pond volume. Sludge accumulation is slower for other lagoons.
- The classic ponds configuration (anaerobic pond + facultative pond + maturation ponds) usually reaches complete removal of protozoan cysts and helminths eggs.
- Mosquitoes and similar insect vectors can be a problem if emergent vegetation is not controlled.
- Facultative ponds have good resistance to temporary organic overloads.
- Maturation ponds achieve a high reduction of solids, BOD and pathogens and high nutrient removal if combined with algae harvesting (Tilley et al. 2014) and should reach high coliform removal efficiency (3–4 Ulog).

TECH SHEET #7

Aerated Lagoons (AL)

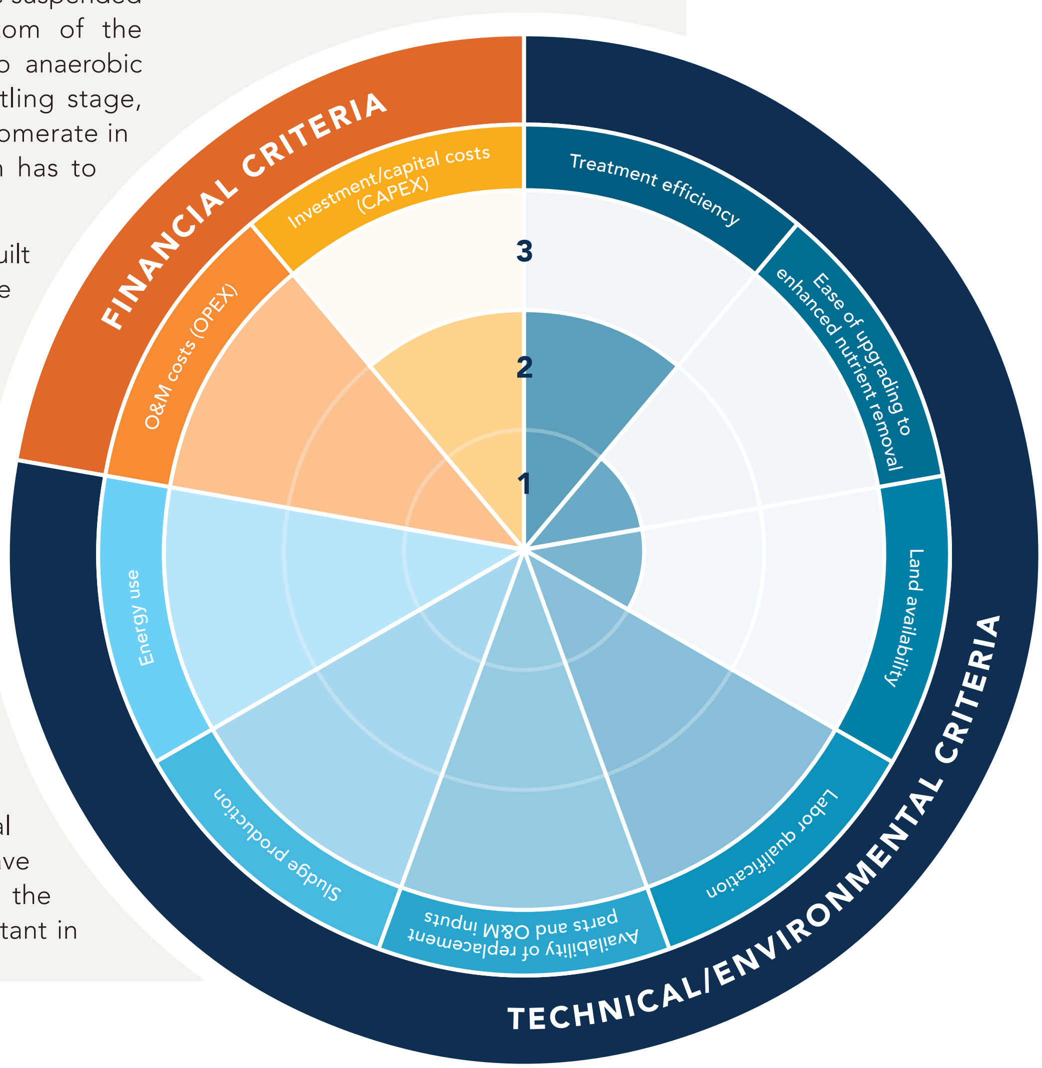
DESCRIPTION

Secondary aerobic treatment
The aerated lagoon (also known as aerated pond) consists of a man-made pond receiving mechanical aeration. This process mirrors the natural treatment occurring in a river body but is aided through mechanical or diffused aeration. The oxygen promotes organic degradation and nutrient removal.

The wastewater flows in continuously and solids are maintained in suspension by the aeration. Dissolved oxygen and suspended solids are maintained uniform throughout the basin. If aeration is maintained in the upper layer only, the pond is called a facultative aerated lagoon. In that case, a portion of the suspended solids settle to the bottom of the basin, where they undergo anaerobic decomposition. In the settling stage, the suspended solids agglomerate in the form of sludge, which has to be regularly extracted.

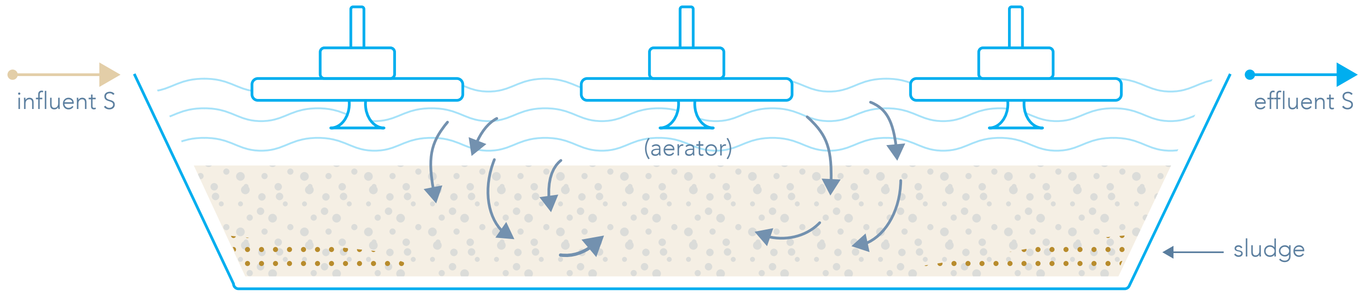
Aerated lagoons can be built in series for most effective treatment, with modulated aeration along the series. The wastewater first goes through the facultative lagoon and the effluent is then polished in an aerated or high performance aerated lagoon. Facultative lagoons are larger, shallower and less aerated than high performance aerated lagoon.

The aerated lagoon is particularly adapted to communities where artisanal or industrial activities have a significant influence on the nature of the organic pollutant in the wastewater. The treatment of wastewater by lagoon processes is characterized by its high buffering capacity with respect to variations in organic or hydraulic loads, due to its hydraulic retention time being much higher than that of other processes.



REUSE POTENTIAL

- Treated water can be used for restrictive irrigation (fruit trees, industrial crops).
- Effluent requires disinfection treatment for non-restrictive reuse.



PROJECT

- **Connected population:**
  (Cluster of houses) or
  (Town)
- **Water and power supply:** No need for continuous water supply. Continuous energy supply is required to operate the aeration mechanism.
- Mixed wastewater flow with organic industrial wastewater is accepted, as are variations in organic or hydraulic loads.

DESIGN

- Work best in series.
- Requires relatively large areas of land, and therefore is still best suited for peri-urban areas or large, rural settlements.
- As the process is resistant to organic and hydraulic shock loads, no equalization step is needed.

OPERATION

- The power level needed to maintain uniform dissolved oxygen in the basin—or top layer of the basin—depends on the aeration equipment (if any) and the influent quality.
- Energy use will be higher for aerated than for facultative aerated lagoons.
- The sludge must be removed from the aerated pond, or from the subsequent sedimentation pond, for continued performance.

TECH SHEET #8

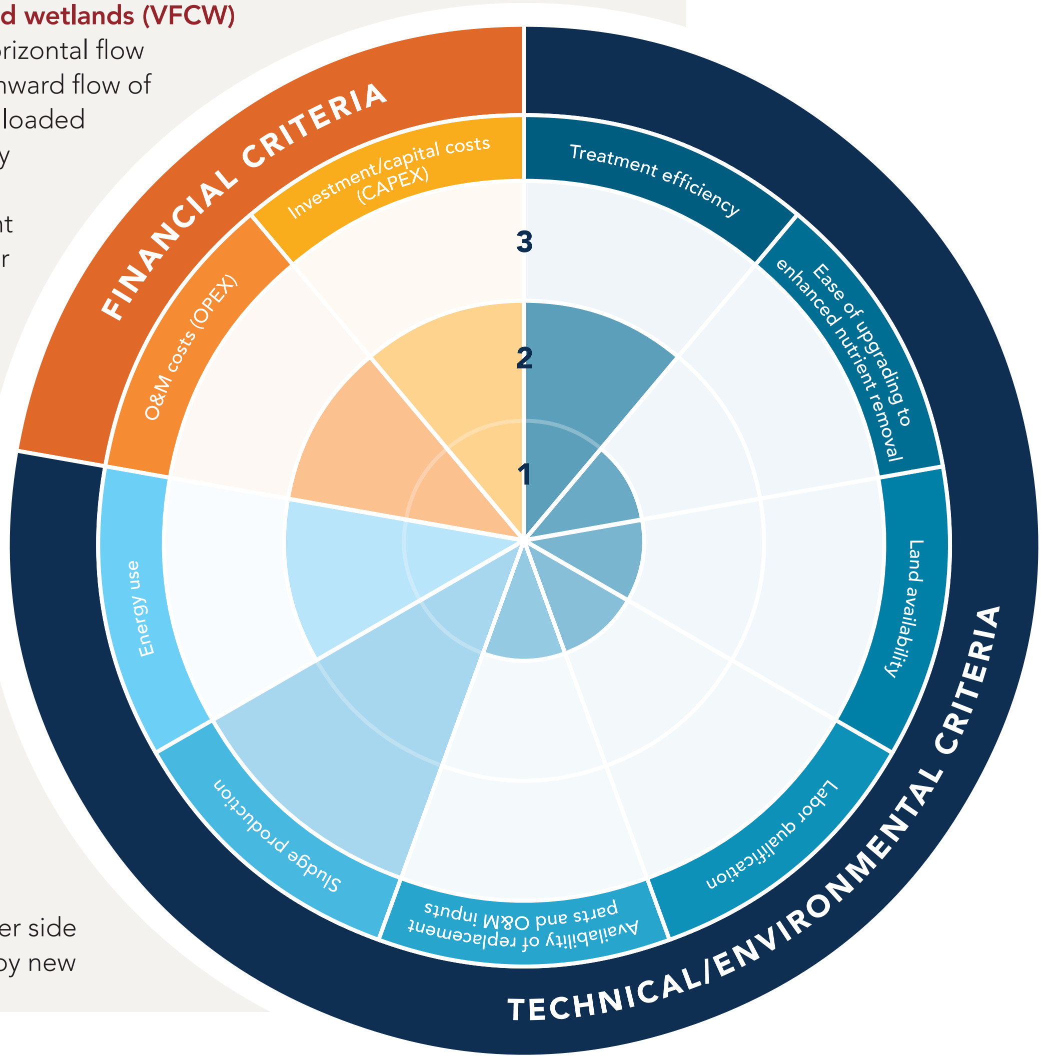
Single-Stage Constructed Wetlands (CW 1-stage)

DESCRIPTION

Secondary aerobic treatment

Constructed wetlands are man-made areas mirroring the structure of natural wetlands to take advantage of natural treatment processes for wastewater. They consist in a porous layer of rock, gravel or sand and a planted bed. The porous layer performs filtration functions and traps some of the suspended solids. The planted bed absorbs some of the pollutants and promotes the development of invertebrates and micro-organisms that further treat the water as it flows through by degrading the organic pollutants. Nutrients are also taken up by microorganisms and plants. The bottom is usually lined with an impermeable liner to control wastewater flow and protect the surrounding area. Constructed wetlands can be distinguished according to criteria such as hydrology (water surface flow and subsurface flow), macrophyte growth form (emergent, submerged, free-floating and floating leaved plants) and direction of flow (horizontal and vertical).

- **Vertical flow constructed wetlands (VFCW)** require less area than horizontal flow wetlands given the downward flow of the wastewater, which is loaded from the top as uniformly as possible to allow for oxygenation. Intermittent loading, using a pump or siphon, further increases the oxygenation and aerobic phase. An anaerobic phase then follows once the wastewater infiltrates further into the medium and until it is collected and discharged at the bottom of the system.
- In **horizontal flow constructed wetlands (HFCW)**, wastewater flows horizontally through the basin and undergoes filtration as it makes its way to the other side of the wetland, pushed by new



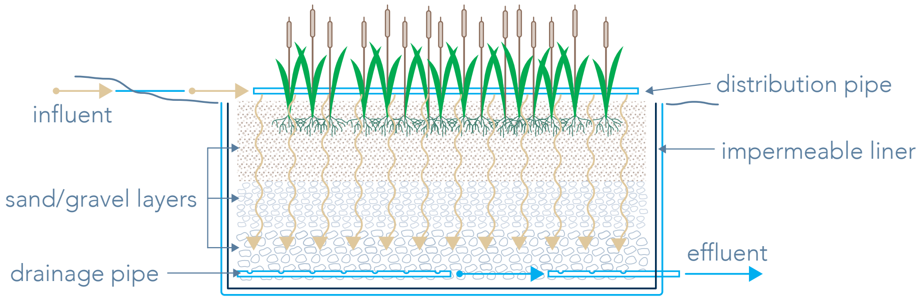
influent. The vegetation transfers a small amount of oxygen to the root zone so that aerobic bacteria can colonize the area. The soil remains saturated, providing limited nitrifying capacity compared to vertical flow constructed wetlands. However, mechanisms to feed the wastewater into HFCW are simpler, making them the preferred choice unless nitrification is required to meet discharge standards.

- In **free water surface constructed wetlands (FWSCW)**, water flows above ground and plants are rooted in the sediment layer at the base of the basin or floating in the water. Compared to subsurface wetlands (horizontal flow or vertical flow), FWSCW can be vegetated with emergent, submerged and floating plants. In these systems, the water surface of the wetland is exposed to the atmosphere which can theoretically provide oxygen to the water and UV disinfection.

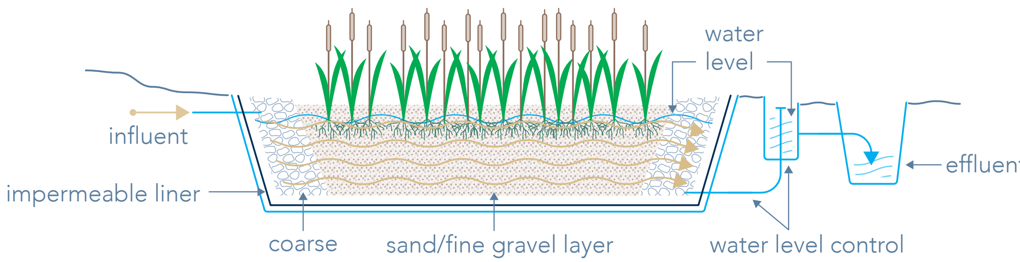
REUSE POTENTIAL

- Effluent not fit for unrestricted reuse but fit for restricted irrigation (trees, crops eaten cooked).
- Treated wastewater can be discharged in stream.

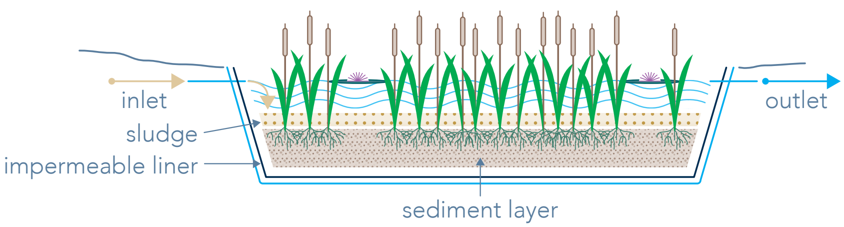
Vertical flow constructed wetlands (VFCW)



Horizontal flow constructed wetlands (HFCW)



Free water surface constructed wetlands (FWSCW)



PROJECT

- **Connected population:** (Cluster of houses) or (Town)
- **Power supply:** When using a pump for wastewater loading, will require electricity supply on a set schedule. Works with both continuous and intermittent wastewater inflow.
- Mixed wastewater flow is not recommended.

DESIGN

- Typical depths range from 0.5 to 1.0 m for HFCW, from 0.8 to 1.4 m for VFCW and 0.15 to 0.60 m for FWSCW.
- Wetland species of all growth forms have been used in constructed wetlands. However, the most commonly used species are robust species of emergent plants, such as the common reed, cattail and bulrush.
- The main function of the plants is to counteract clogging of the filter.
- VFCW will require a pump or sufficient gradient for a siphon pulse-loading system.
- Oxygen transfer rates can be improved by using sand and/or gravel beds and ensuring intermittent loading, so that the beds are not water saturated.
- In HFCW, the outlet should be variable so that the water surface can be adjusted to optimize treatment performance.
- FWSCW typically require a larger area than subsurface systems (HFCW and VFCW), as the porous subsurface filter medium in subsurface systems provides a greater contact area for treatment activities.

OPERATION

- In VFCW, 4 to 10 times a day feeding of wastewater, whereas HFCW is continuous.
- For HFCW, the water level in the wetland is maintained at 5 to 15 cm below the surface to ensure subsurface flow and avoid bad smells.
- The quantity of sludge is affected by the liquid temperature but remains below that of other secondary treatment processes.
- The vegetation transfers a small amount of oxygen to the root zone so that aerobic bacteria can colonize the filter media.
- The risk of mosquito breeding is reduced in HFCW compared to VFCW and FWSCW since there is no standing water.
- In HFCW, the filter material at the inlet zone will require replacement every 10 or more years.

TECH SHEET #9

Hybrid Constructed Wetlands (CW-Hybrid)

DESCRIPTION

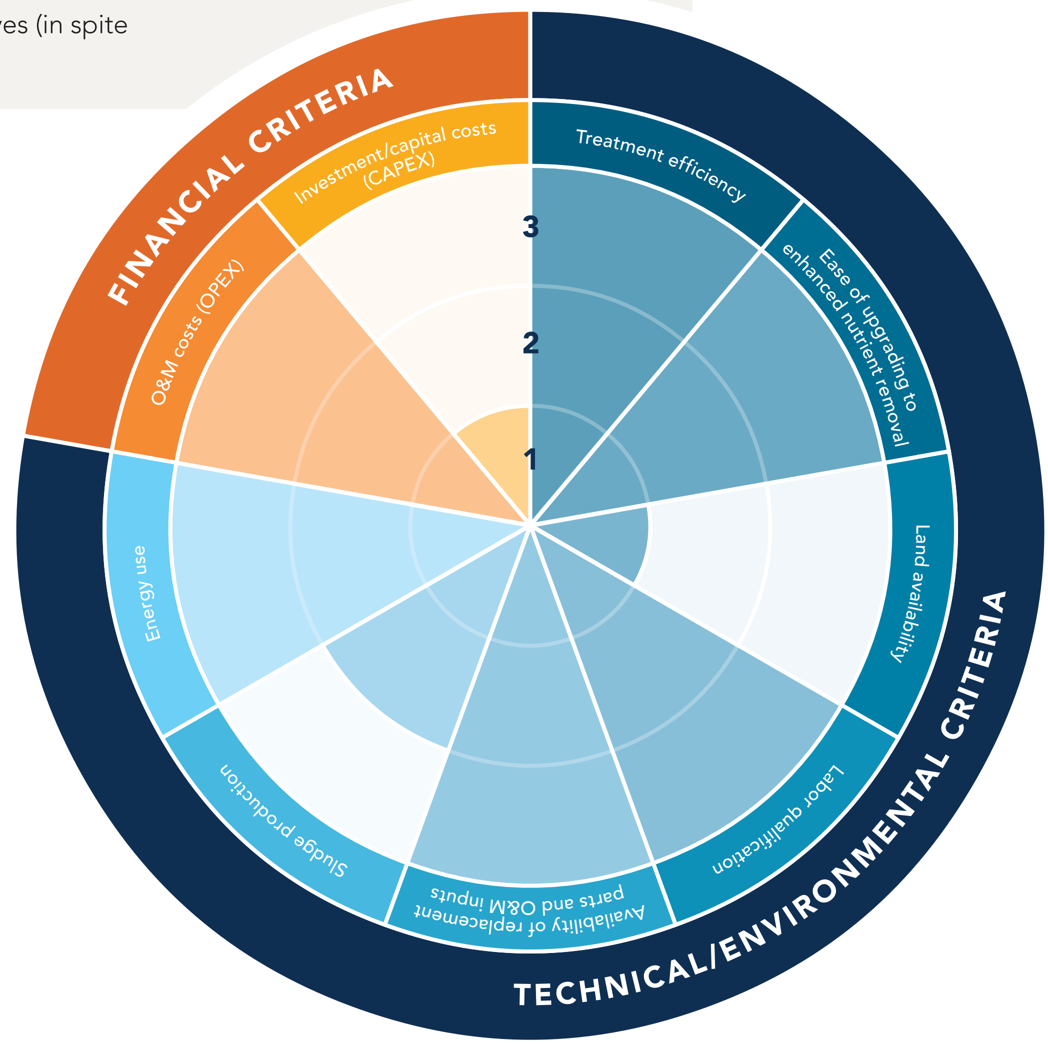
Secondary aerobic treatment

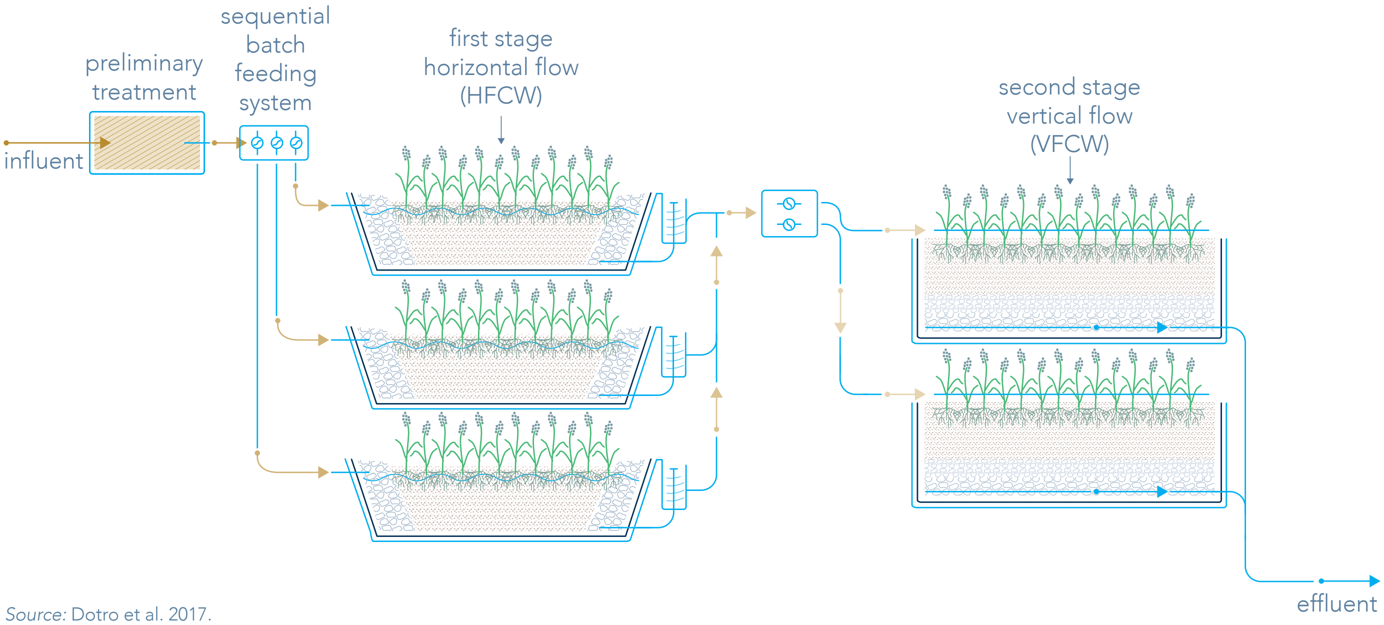
Hybrid Constructed Wetlands (Hybrid CWs) make primarily use of the components described in the Technology Sheet on 1-stage CWs, i.e. horizontal flow CW (HFCW) and vertical flow CW (VFCW). At least 2 of such components are employed in series, but also 3, 4 or even more stages are sometimes used. This brings about distinctive advantages, as compared to 1-stage CWs, such as:

- Total land requirement is reduced to roughly 50% of 1-stage CW. A common plant footprint of Hybrid CWs equals 2.0–2.5 m2/capita in moderate climates, possibly less in hot climates.
- Treatment efficiency becomes more stable, and even improves (in spite of smaller footprint).
- Hybrid CWs can be designed for enhanced biological nutrient removal (BNR). The VFCW in such designs usually serve for nitrification, the HFCW usually serves for denitrification.

REUSE POTENTIAL

- Effluent not fit for unrestricted reuse but fit for restricted irrigation (trees, crops eaten cooked).
- Treated wastewater can be discharged in stream.





Source: Dotro et al. 2017.

PROJECT

- **Connected population:** (Cluster of houses) or (Town)
- **Feasibility of sewerage:** sufficient water supply needed.
- **Fecal sludge:** not suited for direct treatment of fecal sludge; but can be applied after effective primary treatment such as BAR.
- **Regulations for treated discharge & reuse:** high-quality secondary treatment level can be achieved; better disinfection than in most other secondary treatment technologies.
- **Available land for WWTP:** relatively high footprint (even though less than 1-stage CW).
- **Power supply to WWTP:** usually only needed for wastewater pumping; but mere gravity flow is possible in case of advantageous topography.

DESIGN

- For construction details typical characteristics described in the Technology Sheet for 1-stage CWs apply with small modifications, e.g. use of slightly coarser gravel in the first stage.
- For design maximum permitted load criteria for hydraulic and organic loading need to be considered. Treatment efficiency can be derived via kinetic parameters.

OPERATION

- The same principles apply as for 1-stage CWs. That means, O&M is very easy, and does not require particular qualifications.

TECH SHEET #10

Upstream Anaerobic Sludge Blanket reactor (UASB)

DESCRIPTION

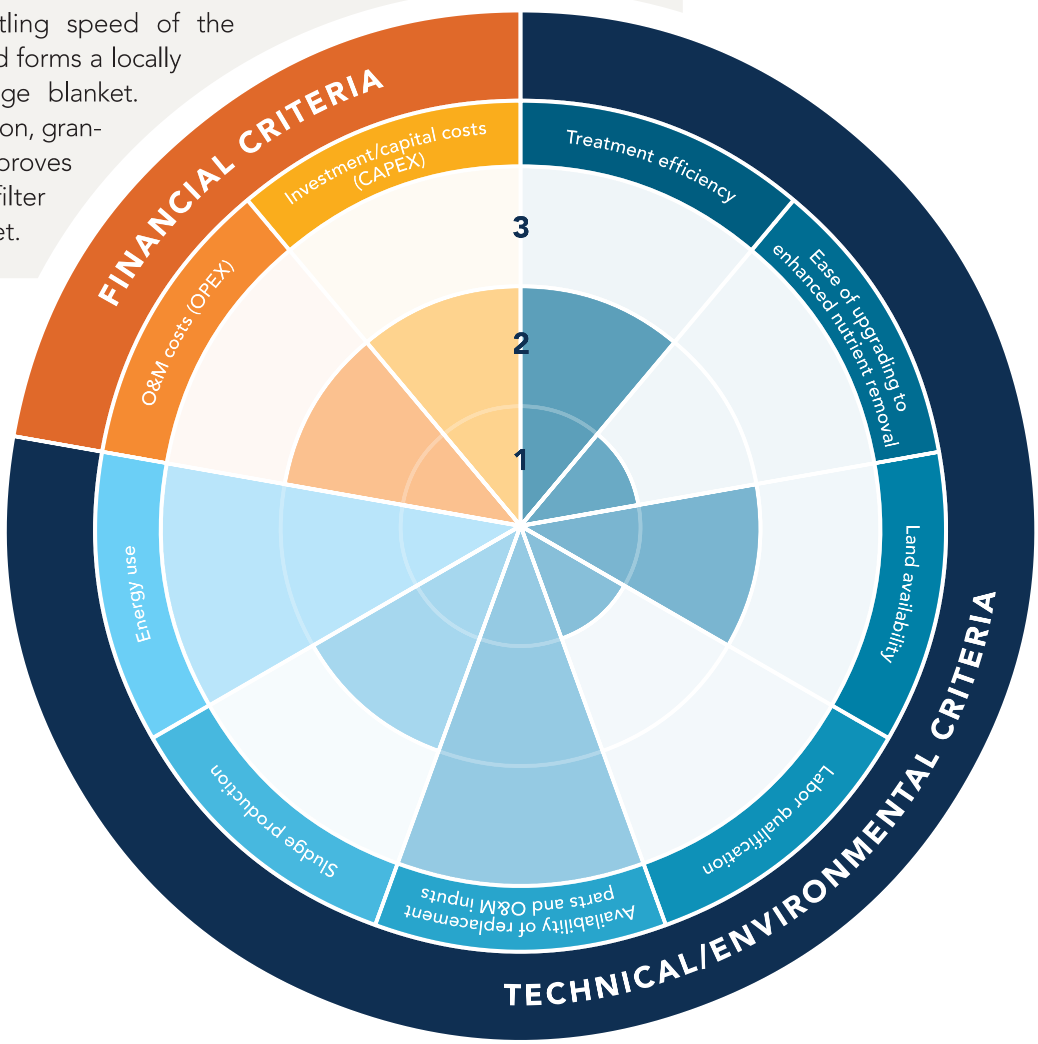
Primary anaerobic treatment

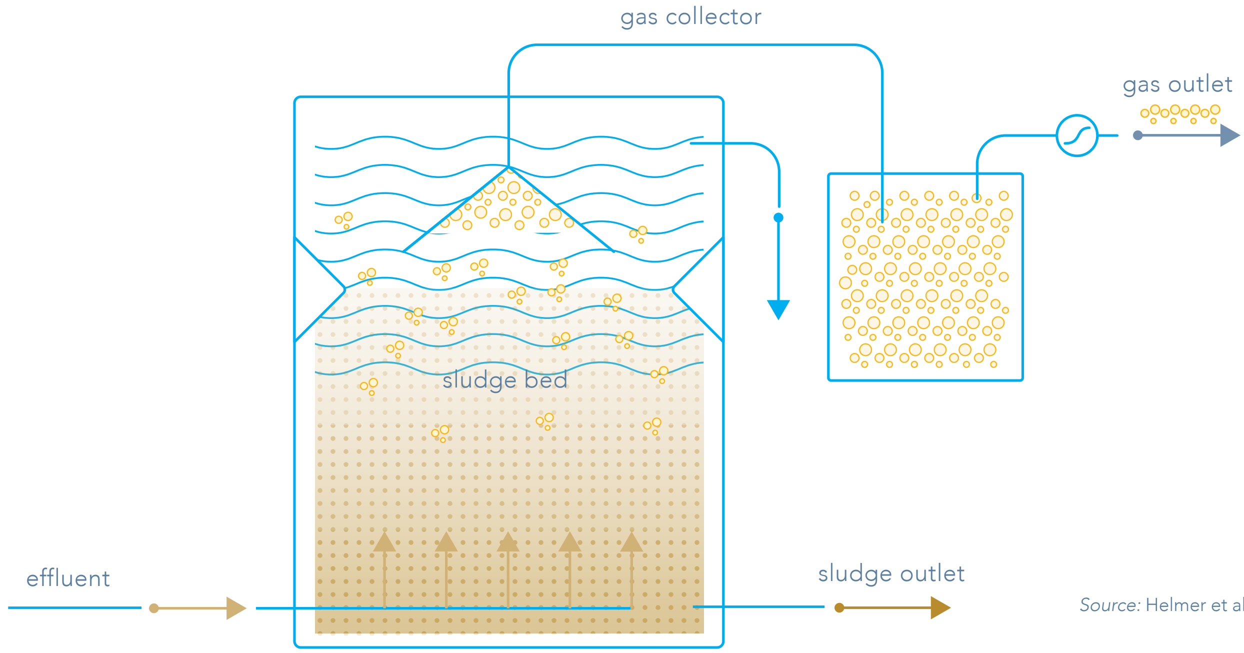
The Upstream Anaerobic Sludge Blanket (UASB) reactor consists in a tank at the bottom of which a 'sludge blanket' forms and anaerobic digestion takes place. Wastewater is introduced as uniformly as possible over the reactor bottom, passes through the sludge bed, and enters the settling zone where solids will further settle. The active sludge is suspended in the lower part of the digester and serves directly as a filter medium. This blanket is made of granular sludge where anaerobic bacteria thrive and process the wastewater as it flows through it. The most characteristic device of the UASB reactor is the phase separator. This device, placed at the top of the reactor, divides it into a lower part, the digestion zone, and an upper part, the settling zone. Wastewater will enter the settling zone via the aperture of the phase separators as it flows upwards.

Upstream velocity and settling speed of the sludge are in equilibrium and forms a locally stable but suspended sludge blanket. After some weeks of maturation, granular sludge forms which improves the physical stability and the filter capacity of the sludge blanket.

REUSE POTENTIAL

- Treated wastewater can be discharged in ocean or large river only.
- Biogas produced can be used.





Source: Helmer et al. 1997.

PROJECT

- **Connected population:**
  (Cluster of houses) or
  (Town)
- Existing capacity for sludge treatment in a neighboring urban center can help to use this technology. A UASB is not appropriate for small or rural communities without a constant water supply or electricity.
- Mixed wastewater flow is allowed. Appropriate for heavy load urban wastewater and industrial wastewater.

DESIGN

- The technology is relatively simple to design and build but requires several months to mature and to develop sufficient granular sludge for treatment.
- There is no need for primary settling.
- If biogas capture is not a priority, can be built underground to optimize the space and structure.

OPERATION

- To maintain a stable sludge blanket, the flow rate must be controlled and properly geared in accordance with fluctuation of the organic load. In smaller units, it is not possible to stabilize the process by increasing the hydraulic retention time without lowering the upstream velocity.
- The fully controlled UASB is used for relatively strong industrial wastewaters.
- The UASB reactor has the potential to produce higher quality effluent than Septic Tanks and can do so in a smaller reactor volume.
- Sludge production is very low.

TECH SHEET #11

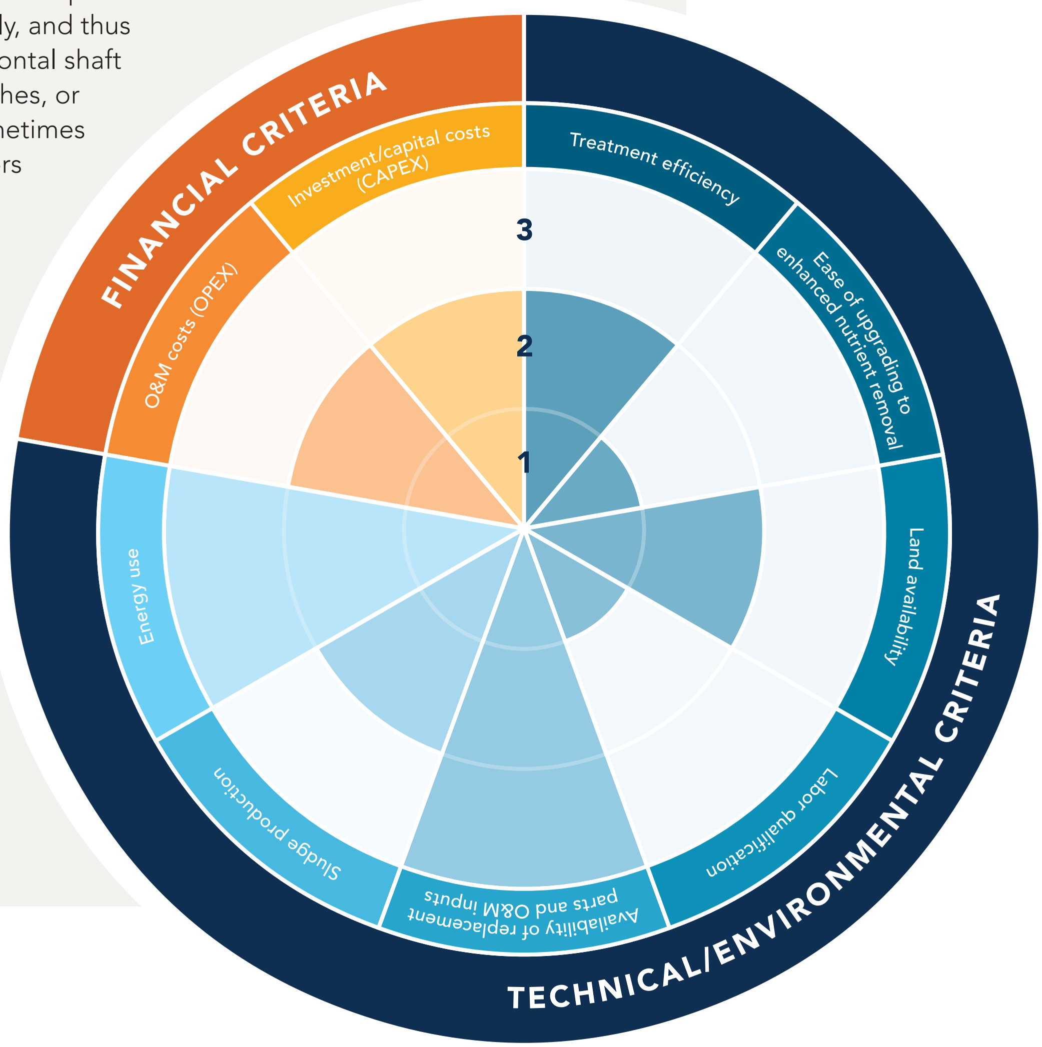
Extended Aeration: Activated Sludge Type (EA)

DESCRIPTION

Secondary aerobic treatment

Extended Aeration (EA) is a well-established variation of the activated sludge process. Contrary to other, more complicated representatives of that process, EA is built around the principle of simplicity. There are no Primary Sedimentation Tanks, and the waste activated sludge is subjected to such long retention times in the aeration tanks, that no sludge digesters are needed for sludge digestion / stabilization. That is, waste sludge removed from the tanks can be directly thickened and dewatered. EA comes in several variations, of which the most common ones are characterized as follows:

- **Oxidation ditch EA:** In this configuration the Aeration Tank is constructed as a closed loop channel, leading to what is called "completely mixed" flow conditions. Typically, water depth is in the order of 2 m only, and thus enables the use of horizontal shaft mechanical aerator brushes, or similar installations. Sometimes also vertical shaft aerators are used, and located at the U-turning point towards the end of those tank loops. The aerators provide the necessary oxygen for microorganisms, and they also provide horizontal thrust to facilitate good mixing conditions. In a subsequent Secondary Sedimentation Tank the sludge flocs are allowed to settle by gravity at the tank bottom, from where the sludge is pumped back to the Aeration Tank.
- **Carrousel type EA:** Similvar to Oxidation Ditches, however employing larger tanks with more U-turns; there are typically 4 lanes. Water depth



is sometimes increased to about 5 m, which facilitates better energy efficiency of aeration.

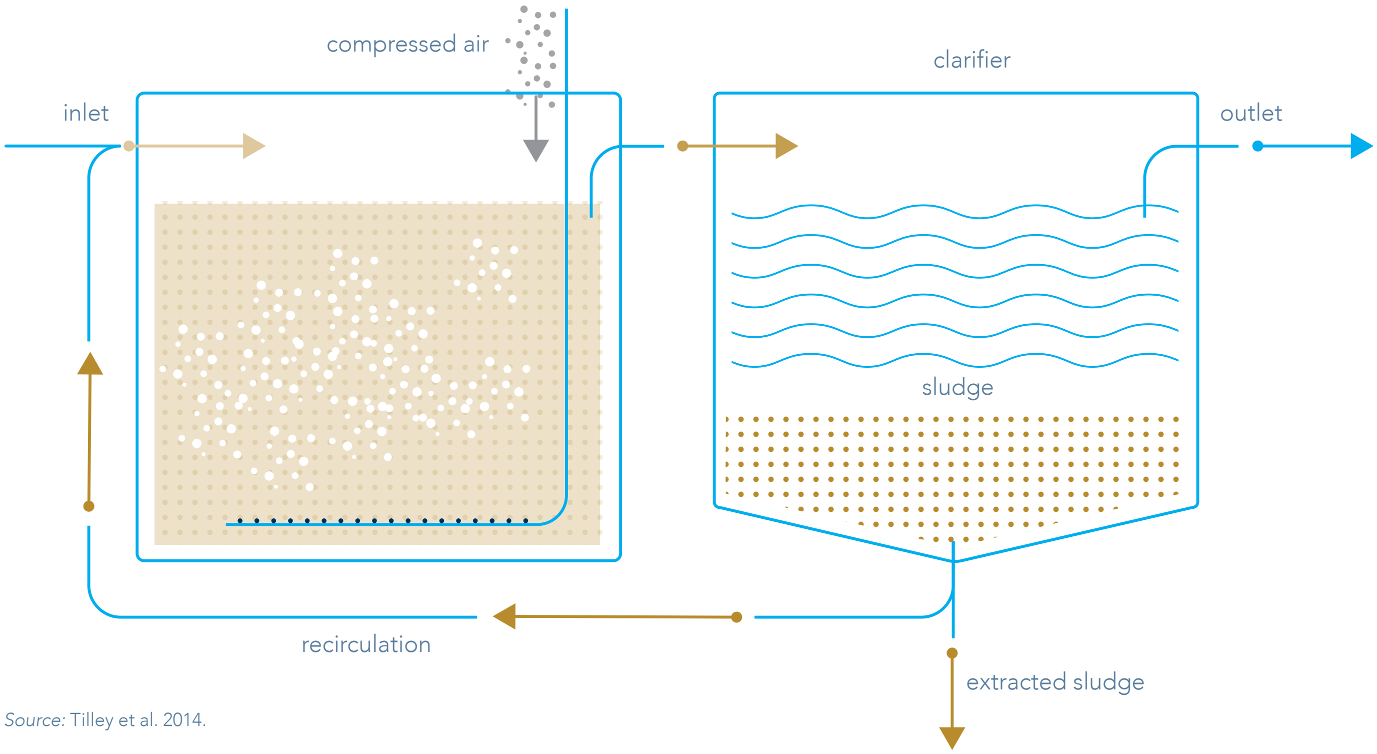
- **Plug-flow EA:** The Aeration Tanks are shaped such that flow enters on one end, and leaves at the other end ("longitudinal" flow, also called "plug-flow" conditions). Mostly this is done to improve efficiency: that is, pressurized aeration is used, water depth is increased to mostly 5–6 m, aerated zones and non-aerated zones are installed intermittently, and smart automation systems for the control of air supply are introduced, complete with effluent quality control sensors and frequency-controlled blowers.
- **SBR type EA:** For this variation a separate Technology Sheet has been prepared, due to the very different flow conditions of that process.

The advantages of EA are a very robust process with large reactor volumes that can also cope with brief organic and hydraulic shock loads. It can be employed in any climate conditions, and it can be designed for any secondary treatment level. Due to economy of scale effects on cost, this technology should not be considered for very small facilities.

Disadvantages are a requirement for sound process understanding by operators, regular maintenance needs, high energy consumption for aeration, high OPEX and CAPEX, and a risk of the formation of filamentous micro-organisms, which negatively hamper sedimentation and may thus seriously affect treatment efficiency.

REUSE POTENTIAL

- Effluent not fit for irrigation.
- Treated wastewater can be discharged in stream.



Source: Tilley et al. 2014.

PROJECT

- **Connected population:** (Town)
- **Feasibility of sewerage:** sufficient water supply needed.
- **Fecal sludge:** only very limited volumes of fecal sludge can be co-treated.
- **Regulations for treated discharge & reuse:** high-quality secondary treatment level can be achieved.
- **Available land for WWTP:** small footprint.
- **Power supply to WWTP:** high (particularly for aeration, but also for pumping purposes); constant and reliable power supply needed.

DESIGN

- The aeration tank volume sizing is done such that the sludge stays sufficiently long in the Aeration Tank so that it can be considered stabilized (represented by what is called "high aerobic sludge age," or "high aerobic sludge retention time (SRT)," or "low F/M (food/ microorganisms) ratios").
- Typical design values are SRT in a range of 15–25 days, with cold climates in the upper range, and warm climates towards the lower range.
- The Secondary Sedimentation Tanks are designed as classical sedimentation tanks, based on parameters such as retention time and hydraulic surface charge.

OPERATION

- O&M requires process understanding by well-trained staff. This involves finding the right balance between incoming pollution loads and adequate biomass, and at the same time permitting stabilization of the sludge. But also appropriate control of the sludge depth in the sedimentation stage is needed, and appropriate and fast trouble-shooting to sludge sedimentation problems may be necessary, too.
- Regular maintenance of pumps and aeration system (diffusers + blowers, or mechanical aerators) is needed.

TECH SHEET #12

Extended Aeration: Sequencing Batch Reactor Type (SBR-EA)

DESCRIPTION

Secondary aerobic treatment

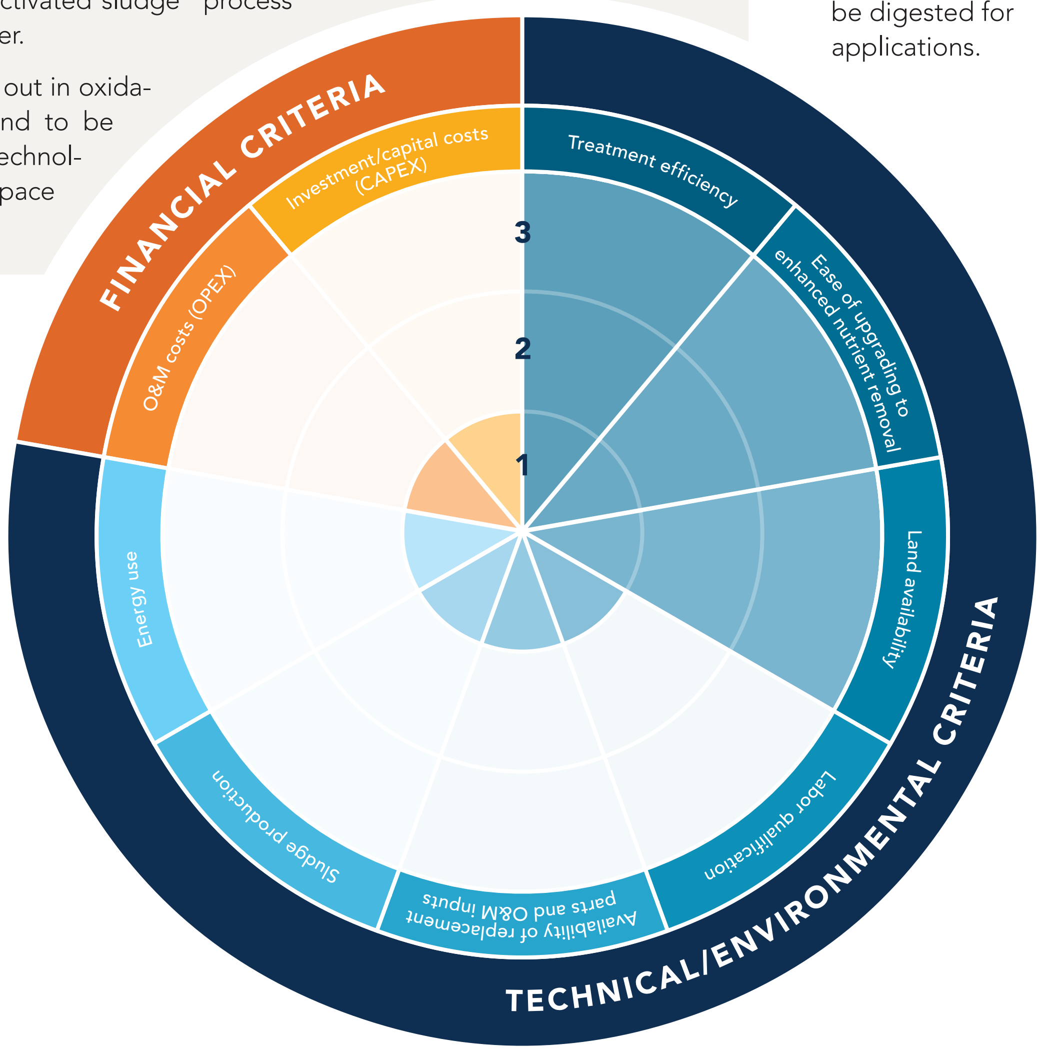
The sequencing batch reactor (SBR) constitutes a particular variant of activated sludge and in the case of small towns is most relevantly used for extended aeration (EA). EA applies best to smaller waste loads and requires longer mixing times given that all processes (agitation of sludge and decantation) occur in the same clarifier, leading to high sludge age. The SBR follows the same basic principles as activated sludge: biological treatment, such as the formation of suspended biomass, the concentration of biomass in the reactor and the separation of biomass from the treated effluent. The special feature of this variant is that the settling of the biomass is carried out directly in the aeration tanks rather than in a separate clarifier.

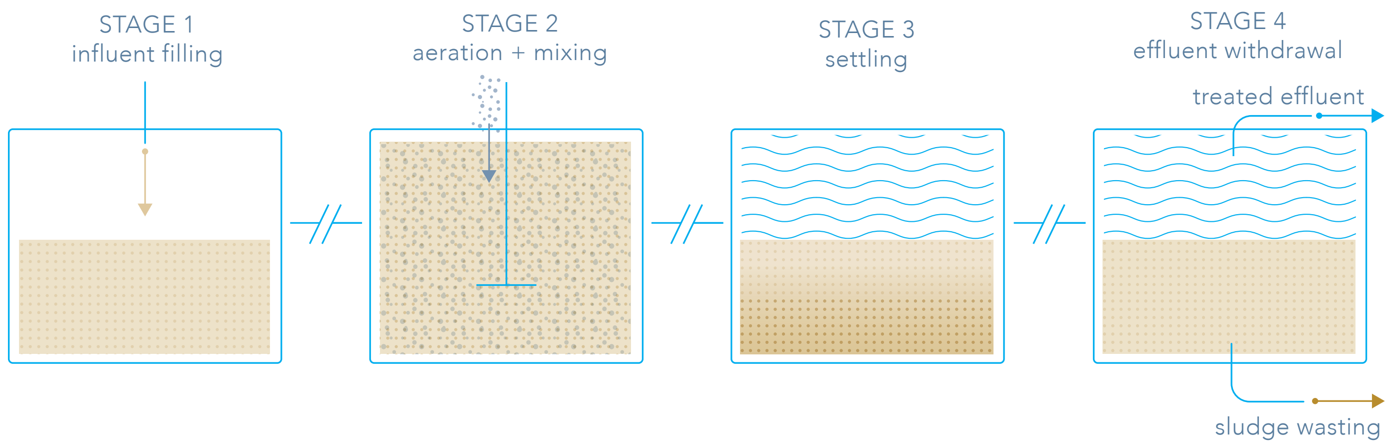
The process operates in batch mode in a sequence typically comprising the following phases: filling, reaction (aeration and mixing), decantation, and withdrawal of the supernatant or effluent. The performance of this system is theoretically equivalent to the conventional "activated sludge" process associated with a clarifier.

EA can also be carried out in oxidation ditches, which tend to be considered an older technology and require more space than SBR.

REUSE POTENTIAL

- Treated water can be used for restrictive irrigation (fruit trees, industrial crops).
- Effluent requires disinfection treatment for non-restrictive reuse, and filtration and disinfection for reuse by drip irrigation.
- Sludge needs to be digested for applications.





PROJECT

- **Connected population:**
  🏠🏠 (Cluster of houses) or
  🏠🏠 🏠 (Town)
- **Power supply:** Requires continuous electricity supply. Functionality with low loads must be evaluated where there is a combined sewer system.
- Mixing incoming wastewater with industrial wastewater could impact treatment performance. Resistant to shocks in organic and hydraulic loading.

DESIGN

- To optimize the performance of the system, two or more batch reactors are used in a predetermined sequence of operations.
- SBR are typically used at flowrates of 20.000 m^3/d or less but the most SBR installations are used for smaller wastewater systems of less than 8.000 m^3/d.
- Flexible sizing means potential population growth can be considered at design.
- Potential capital cost savings by eliminating clarifiers and other equipment.

OPERATION

- The choice of SBR-EA is not recommended for applications where the wastewater is diluted or where there is a high flow of parasitic water.
- The choice of SBR is not recommended for irregular applications with periods of low loads or absence of loads which could lead to deterioration of the biomass, though sometimes it is complemented with additional feed in low load periods.
- Potential plugging of aeration devices during selected operating cycles.
- Due to the high level of sophistication and complexity of the process, not all parts and materials may be locally available.

TECH SHEET #13
Trickling Filter (TF)

DESCRIPTION

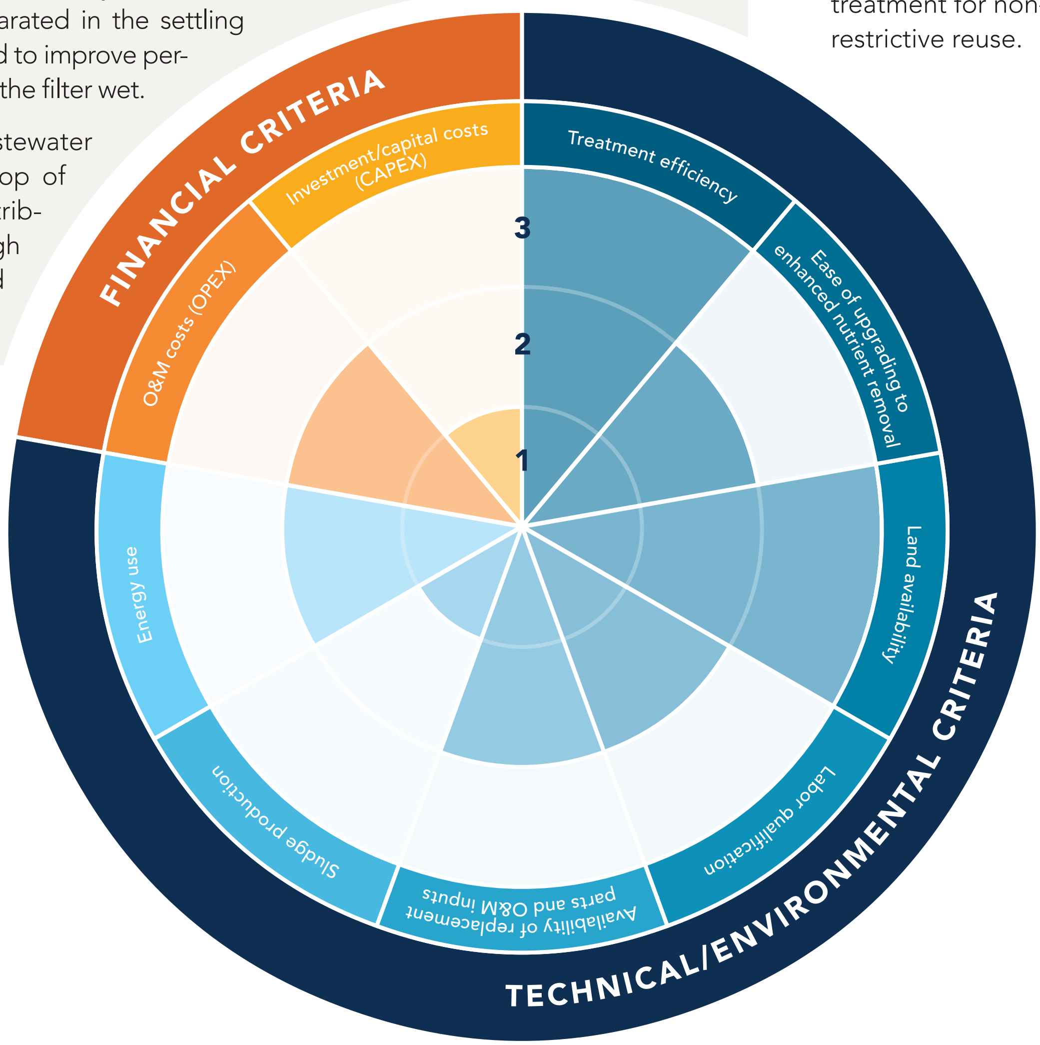
Secondary aerobic treatment

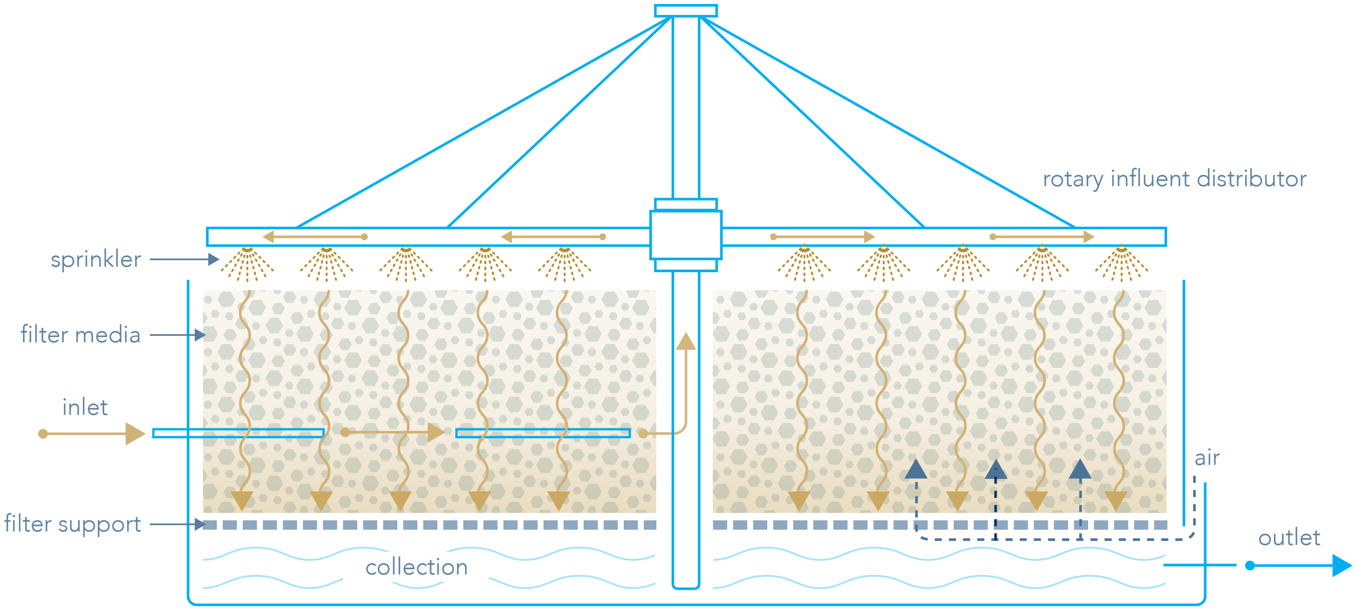
Trickling filters consist in a structure containing a substrate (rocks, gravel, shredded PVC pipes, pozzolana) that acts as support for the development of microorganisms. These form the biological film, which is composed of aerobic bacteria on the surface and anaerobic bacteria deeper in the medium. As previously decanted wastewater is sprinkled and infiltrates through the medium, the biofilm grows around the support and detaches when the water percolates. At the outlet of the trickling filter, the biofilm is trapped by settling in a secondary clarifier and forms sludge. The water separated in the settling tank is often recirculated to improve performance and maintain the filter wet.

In most cases, the wastewater is distributed at the top of the bed by a rotary distributor (sprinkler), though it can also be supplied by gravity.

REUSE POTENTIAL

- Treated water can be used for restrictive irrigation (fruit trees, industrial crops).
- Effluent requires disinfection treatment for non-restrictive reuse.





Source: Tilley et al. 2014.

PROJECT

- **Connected population:** (Cluster of houses) or (Town)
- Continuous flow of influent is important to avoid drying of the biofilm, and continuous energy supply is required if used to transport and/or supply the wastewater. In this sense, continuity of water supply may also affect performance, or require a storage/equalization tank.
- Limited ability to accept mixed wastewater flow. Good resistance to transient organic overloads (50% organic load increase is accepted).

DESIGN

- Best suited for peri-urban or large rural settlements.
- Requires primary clarification to avoid clogging.
- The sprinkler is the most suitable and widely used distribution system with a sufficient flow rate to generate a rotational movement.
- Must be coupled with secondary settler to remove suspended solids.

OPERATION

- Influent distribution must be uniform to allow for treatment and avoid preferential paths.
- Periods of non-supply to the trickling filter lead to its desiccation and are to be avoided.
- Replacement parts are needed for the pumps and the distribution system (sprinkler).
- If influent distribution is done with gravity, then there is no energy input need.

TECH SHEET #14

Rotating Biological Contactor (RBC)

DESCRIPTION

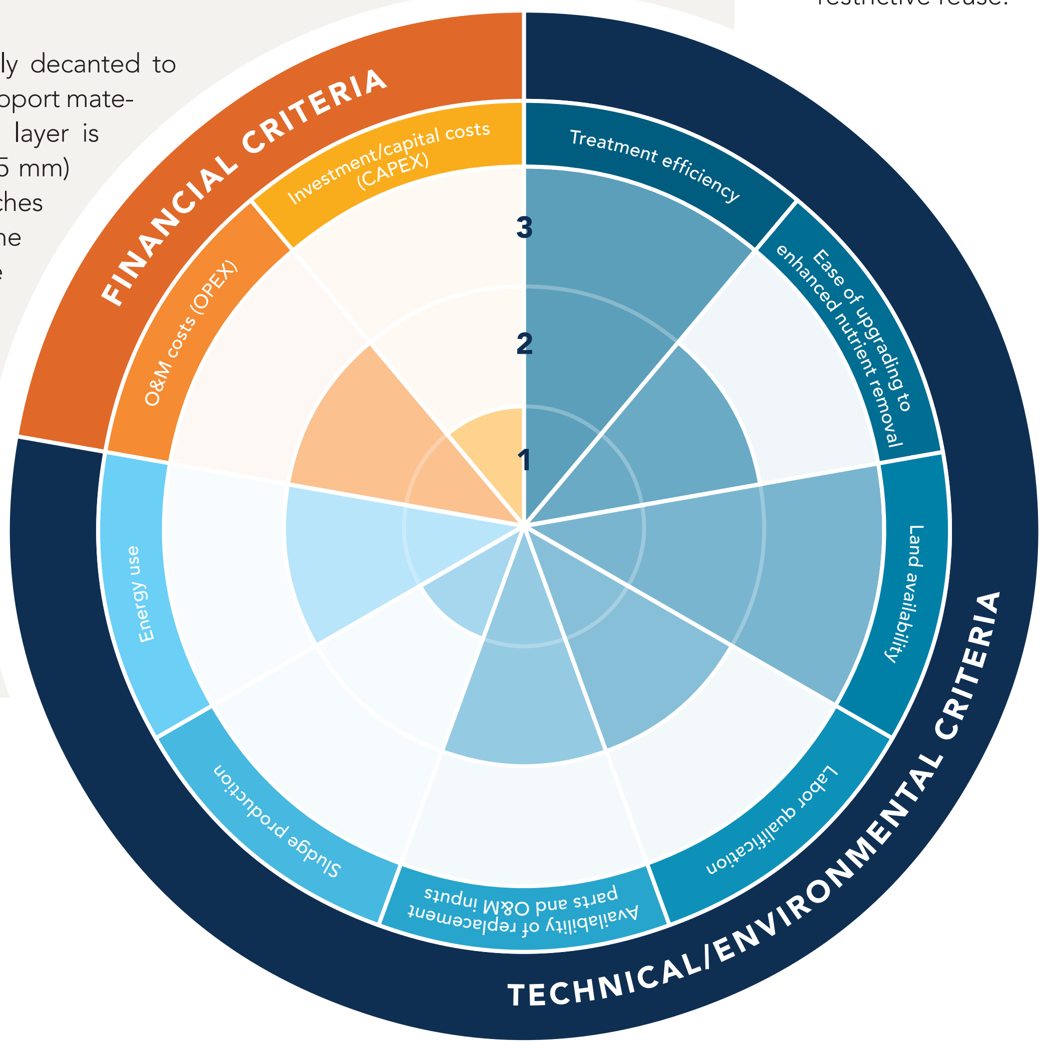
Secondary aerobic treatment

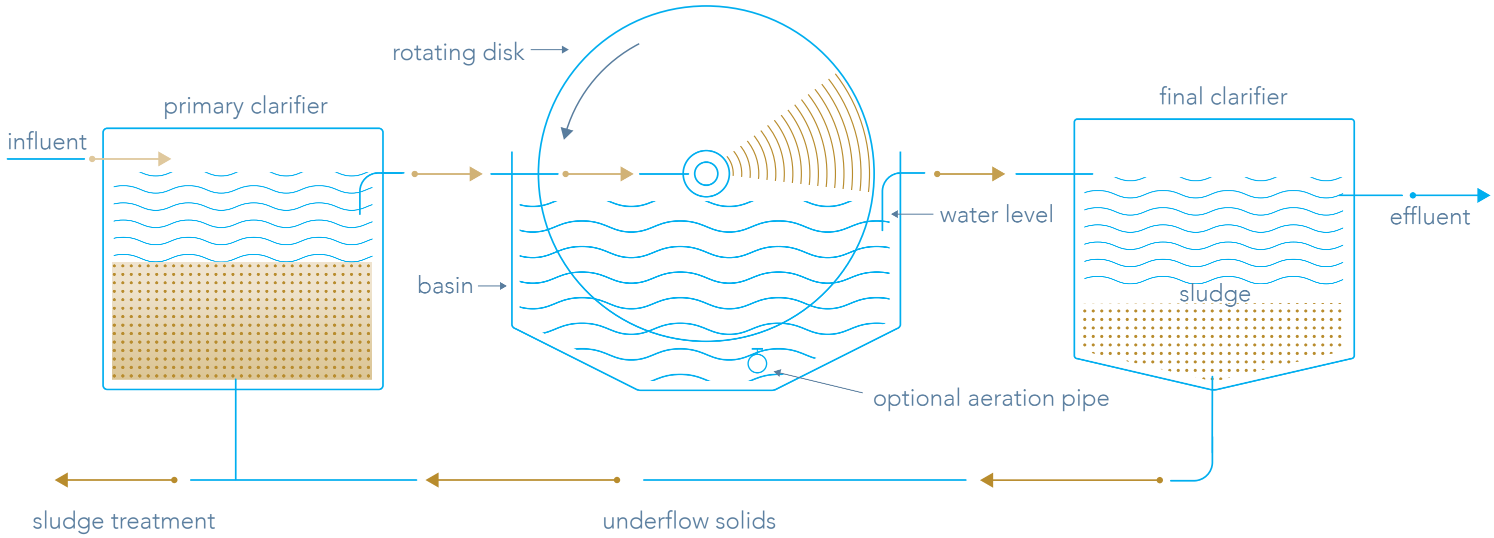
A rotating biological contactor (RBC) is a biological aerobic process. Discs serve as the supports for microflora growth. They are partially immersed in the wastewater and driven by a rotational movement along a horizontal axis, which ensures both mixing and aeration. The microorganisms develop and form an active biological film on the disc surface. The rotation alternates the immersion state of the biomass, allowing both its oxygenation and absorption of organic matter. The rotational speed, which controls the contact intensity between the biomass and the wastewater and the rate of aeration, can be adjusted according to the organic load in the wastewater.

The influent is previously decanted to avoid clogging of the support material. When the biomass layer is sufficiently thick (about 5 mm) some biomass detaches and is deposited at the bottom of the unit. The sludge is separated from the treated water by secondary clarification. The treatment performance is of the same order of magnitude as activated sludge or SBR. Also very effective in the removal of pathogenic bacteria.

REUSE POTENTIAL

- Treated water can be used for restrictive irrigation (fruit trees, industrial crops).
- Effluent requires disinfection treatment for non-restrictive reuse.





PROJECT

- **Connected population**: (Cluster of houses) or (Town)
- **Power supply:** Requires a continuous electricity supply.
- The process is highly stable, resistant to shock hydraulic or organic loading.

DESIGN

- Must be coupled with secondary settler to remove suspended solids.
- Typical arrangement for secondary treatment comprises 3 or 4 stages. In small installations these stages can be on the same shaft, the sections of support medium separated by baffles to produce a series of hydraulically independent compartments.
- The addition of an air injection system to the wastewater in the disc tank is optional.
- If the organic load of the influent is variable, an aerated equalization basin is needed upstream.

OPERATION

- Requires operating personnel with electromechanical skills.
- Additional oxygen supply may be particularly helpful when the loads of the influent are high.
- The sludge from the secondary clarifier must be extracted daily to prevent sludge buildup and effluent losses.
- Must be protected against sunlight, wind and rain (especially against freezing in cold climates).

TECH SHEET #15

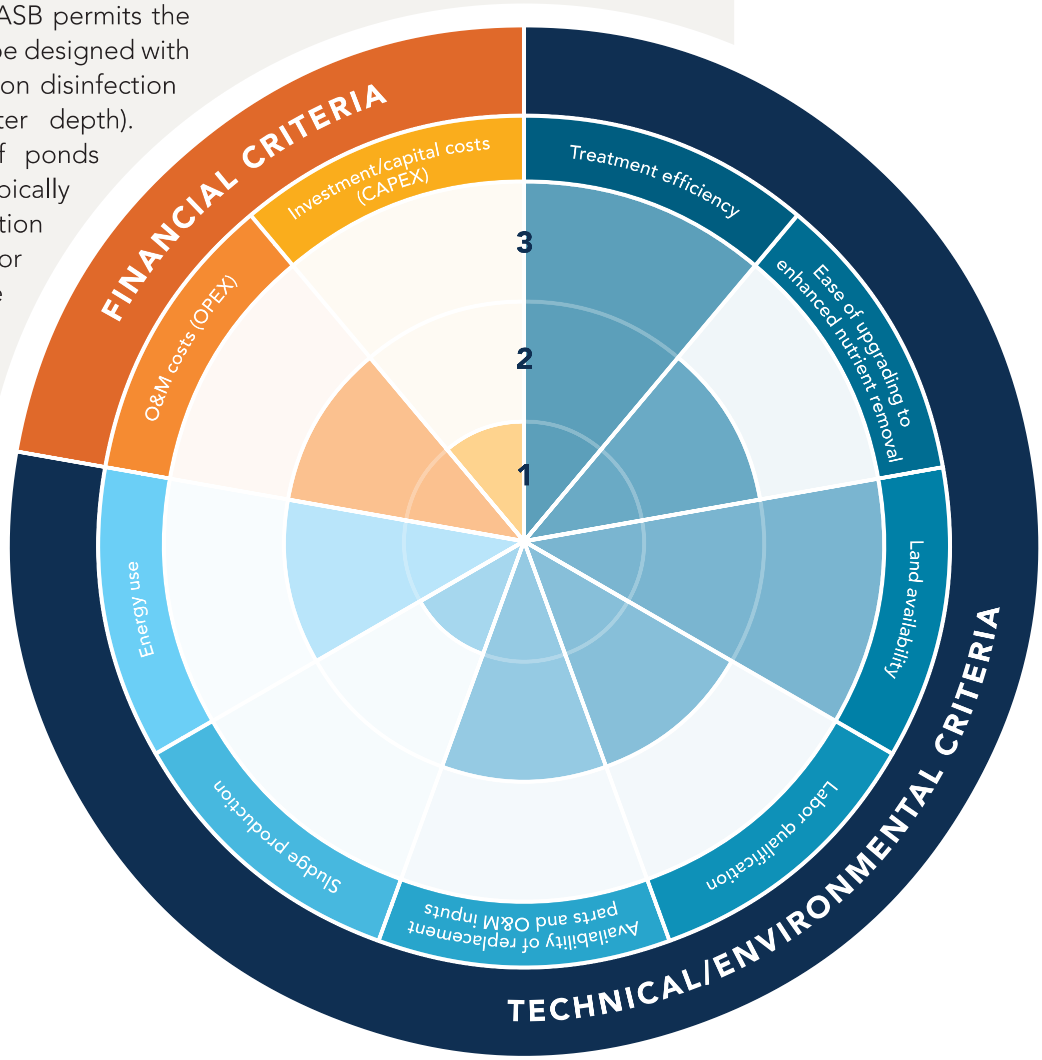
UASB Followed by WSP (UASB-WSP)

DESCRIPTION

Secondary aerobic treatment

The UASB reactor as first biological stage removes the bulk of organic pollution, and the sludge from this stage is well-digested. Combined with the ponds for disinfection and polishing this treatment technology is thus ideal for a focus on removal of organic pollution, combined with disinfection.

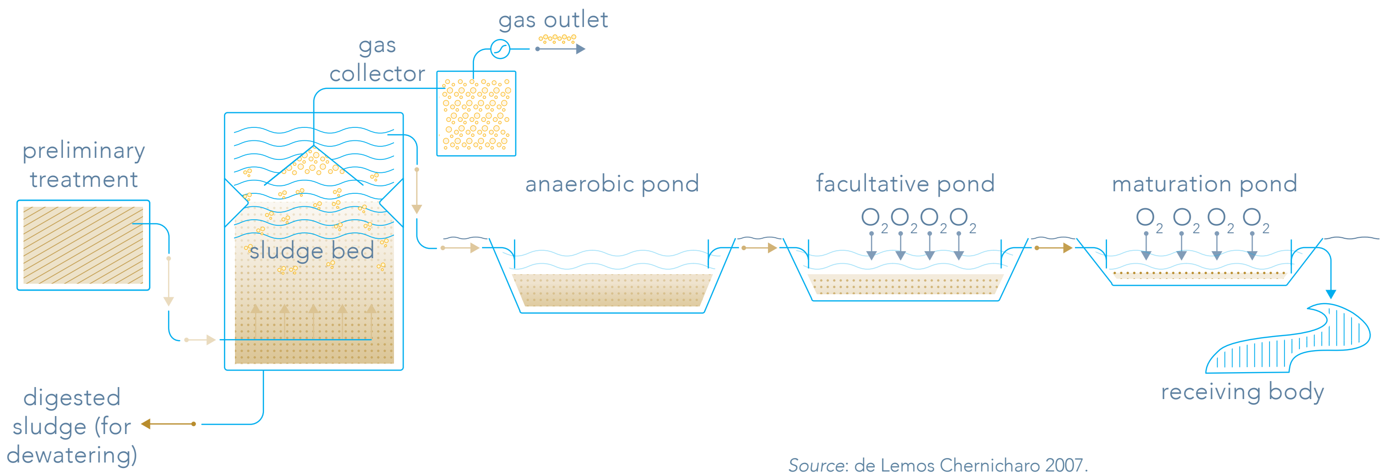
- Several **advantages** exist: Anaerobic sludge yield is generally low, which—combined with the efficient stabilization and thickening inside the UASB reactors—permits for direct cost-efficient sludge dewatering. Fecal sludge can be efficiently co-digested in UASB. The high organic load reduction in UASB permits the polishing ponds to be designed with an optimized focus on disinfection (e.g. optimum water depth). The disinfection of ponds is efficient, and typically no tertiary disinfection stage is needed for direct effluent reuse in non-restrictive irrigation. Sludge removal from the ponds can be limited to prolonged intervals > 10 years frequently. Eventually, the possible use of the biogas from UASB for energy generation may be an attractive side-effect. Taking the low total energy consumption into account, such systems can hence even become energy independent from the public grit.



- **Disadvantages** are that UASB reactors generate biogas, rich in methane, which must be properly managed to minimize risks of explosion. That also implicates a need for well-trained personnel. Further, preliminary treatment must be efficient and well operated, too. If this is not done the formation of scum on the surface of UASB can be considerable; removing such scum from the inside of reactors that are designed to be possibly gas-tight, is a challenge. This challenge is further complicated, since the scum tends to solidify, and then proves hard to remove. Even if the UASB is properly managed, some biogas always remains dissolved in its liquid effluent, and then escapes to the open air, contributing to GHG emissions. Upgrading to BNR can be done, but requires extra stages for nitrification. Finally, it remains to mention that the ponds require considerable land footprint, and are not feasible in case of very limited land availability.

REUSE POTENTIAL

- Effluent is fit for non-restrictive irrigation.
- Due to high algae production, use through drip irrigation requires filtration to remove the suspended solids.
- Treated wastewater can be discharged in stream.



Source: de Lemos Chernicharo 2007.

PROJECT

- **Connected population:** (Cluster of houses) or (Town)
- **Feasibility of sewerage:** sufficient water supply needed.
- **Fecal sludge:** to some reasonable extent fecal sludge can be co-treated in UASB.
- **Regulations for treated discharge & reuse:** secondary treatment level can be achieved; however, organic parameters may even increase in pond effluent due to formation of algae (algal BOD_5 is not the same as raw wastewater BOD_5, but nonetheless is shows up in analysis); nutrient removal is limited.
- **Available land for WWTP:** high footprint, particularly for ponds.
- **Power supply to WWTP:** low; if power is needed, it is primarily for wastewater pumping and for operation of preliminary treatment. Biogas from UASB could be used for energy generation.

DESIGN

- For UASB design see separate Technology Sheet. While there are a series of different parameters that need to be taken into account, for very rough sizing an average retention time of 6–12 hours may be assumed (6 h for wastewater temperature > 26°C, 12 h for 18°C). Typical UASB water depth is 4–6 m.
- The maturation ponds are designed for hydraulic surface charge and retention time (minimum 3–4 days to permit proliferation of algae). Water depth is about 1 m.

OPERATION

- O&M of UASB requires careful attention to keeping preliminary treatment efficient and functional, as well as regular scum removal, and proper biogas management. This is not particularly time-consuming, but requires well-trained operators.
- The maturation ponds only need regular trimming of grass on its embankments and intermittent cleaning.

TECH SHEET #16

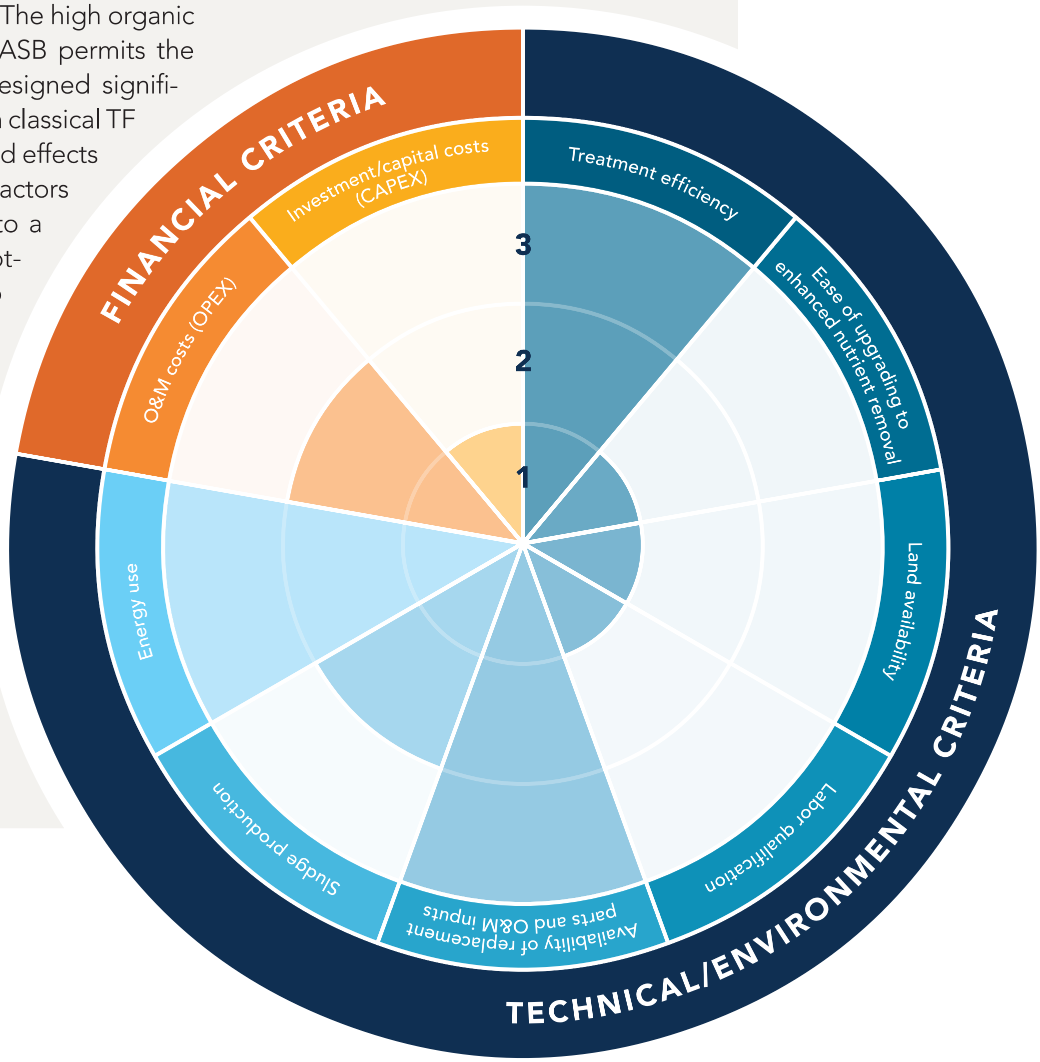
UASB Followed by TF (UASB-TF)

DESCRIPTION

Secondary aerobic treatment

The UASB reactor as first biological stage removes the bulk of organic pollution, and the sludge from this stage is well-digested. Combined with a Trickling Filter (TF) the effluent quality can be further improved, even to BNR standards. For disinfection a tertiary stage is needed.

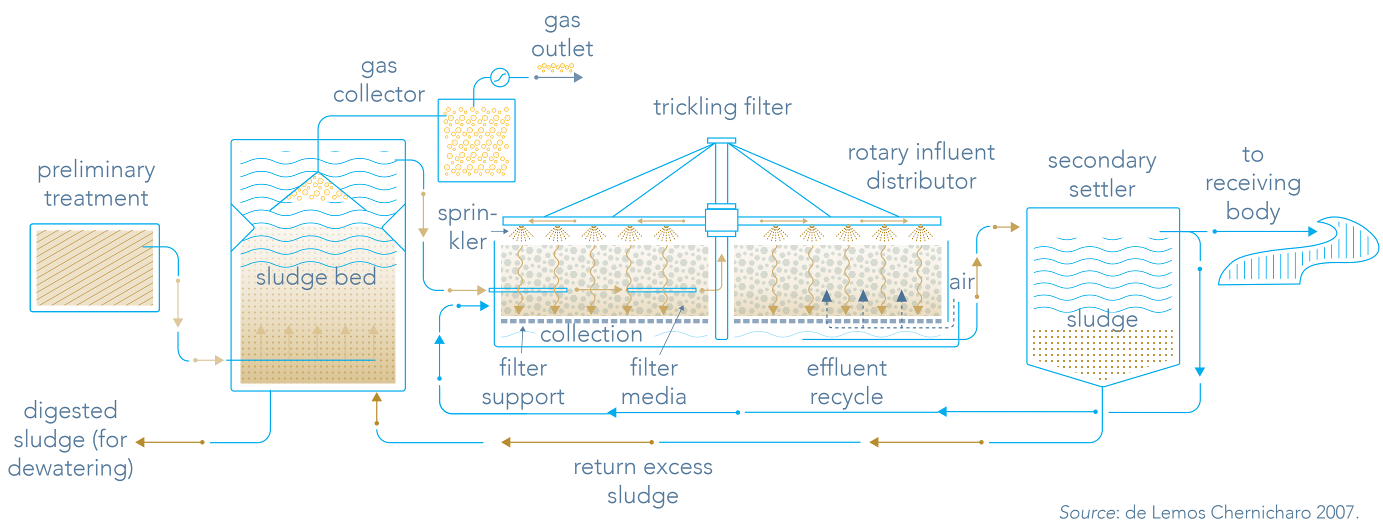
- Several **advantages** exist: Anaerobic sludge yield is generally low, which—combined with the efficient stabilization and thickening inside the UASB reactors—permits for direct cost-efficient sludge dewatering. The waste sludge from the TF stage can also be co-digested in the UASB, as well as fecal sludge. The high organic load reduction in UASB permits the TF volume to be designed significantly smaller than in classical TF plants. The combined effects of 2 high-rate reactors (UASB + TF) leads to a WWTPs with low footprint, comparable to Activated Sludge systems. In addition, such a system with two separate stages can cope well with hydraulic and organic shock-loads in raw wastewater. The possible use of the biogas from UASB for energy generation may be an attractive side-effect. Taking the low overall energy consumption into account, such systems can hence even become energy independent from the public grit, or at least reach a high percentage of power coverage from the biogas.



- **Disadvantages** are that UASB reactors generate biogas, rich in methane, which must be properly managed to minimize risks of explosion. That also implicates a need for well-trained personnel. Further, preliminary treatment must be efficient and well operated, too. If this is not done the formation of scum on the surface of UASB can be considerable; removing suchscum from the inside of reactors that are designed to be possibly gas-tight, is a challenge. This challenge is further complicated, since the scum tends to solidify, and then proves hard to remove. Even if the UASB is properly managed, some biogas always remains dissolved in its liquid effluent, and then escapes to the open air, contributing to GHG emissions. Upgrading to BNR can be done, but requires extra TF volume for nitrification.

REUSE POTENTIAL

- Effluent is fit for restricted irrigation or can be discharged in stream.



Source: de Lemos Chernicharo 2007.

PROJECT

- **Connected population**: 🏠🏠🏠 (Town)
- **Feasibility of sewerage:** sufficient water supply needed.
- **Fecal sludge:** to some reasonable extent fecal sludge can be co-treated in UASB.
- **Regulations for treated discharge & reuse:** secondary treatment level can be achieved; nutrient removal can be incorporated.
- **Available land for WWTP:** low footprint.
- **Power supply to WWTP:** low; power serves primarily for wastewater pumping and for operation of preliminary treatment. Biogas from UASB could be used for energy generation.

DESIGN

- For UASB design see separate Technology Sheet. While there are a series of different design parameters that need to be taken into account, for very rough sizing an average retention time of 6–12 hours may be assumed (6 h for wastewater temperature > 26°C, 12 h for 18°C). Typical UASB water depth is 4–6 m.
- The TFs are designed for volumetric organic loading and hydraulic surface charge, dependent on specific conditions. Filter depth is usually 3–5 m in modern filters.
- Secondary Sedimentation Tanks are designed similar to such installations after Activated Sludge tanks (see e.g. Technology Sheet on EA). Albeit after TFs they can even be designed somewhat smaller due to good settling characteristics of the TF sludge.

OPERATION

- O&M of UASB requires careful attention to keeping preliminary treatment efficient and functional, as well as regular scum removal, and proper biogas management. This is not particularly time-consuming, but requires well-trained operators.
- The operation of the TF stage does not require particular process know-how; however, keeping the electro-mechanical installations well maintained, is not up to unskilled labor.

TECH SHEET #17

Disinfection with Ultraviolet System (UV)

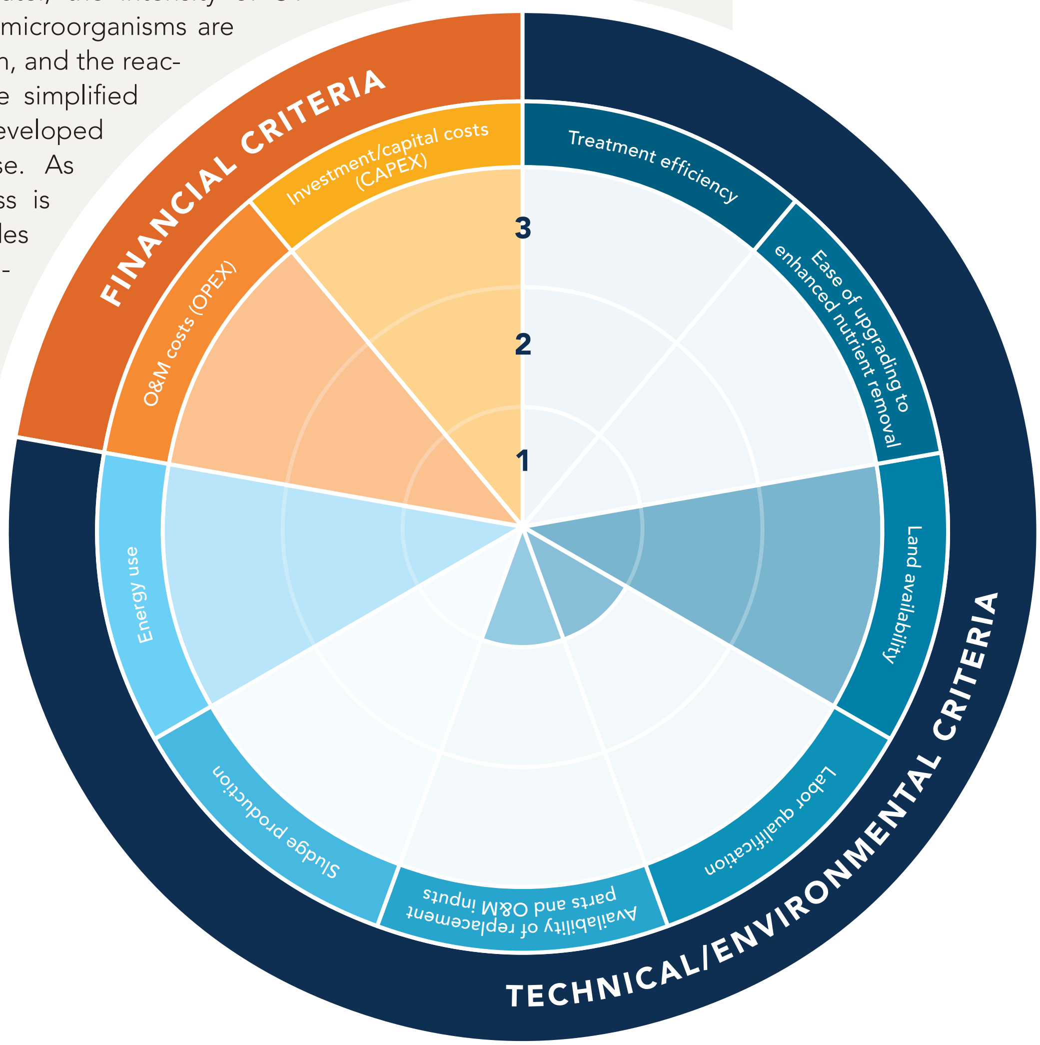
DESCRIPTION

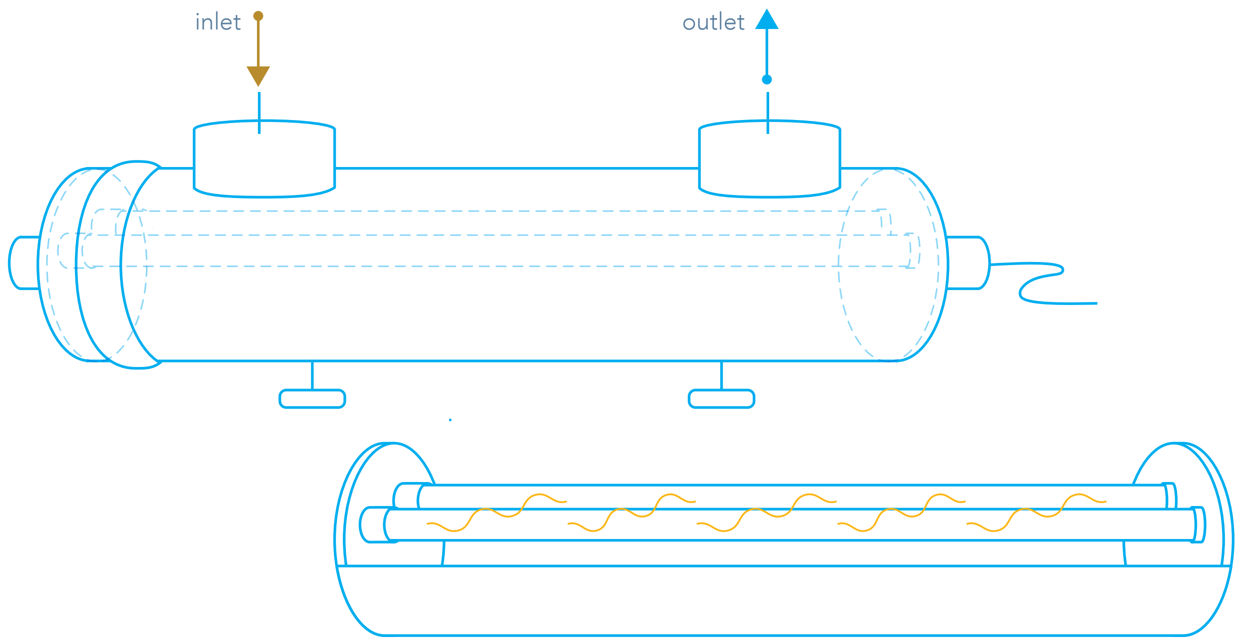
Tertiary treatment, water disinfection

Ultraviolet (UV) disinfection uses mercury arc lamps to expose wastewater to concentrated UV light, which kills pathogenic microorganisms. Wastewater flows perpendicular or parallel to the lamps, which are encased in a protective quartz sleeves (instead of glass) to protect them from the cooling effects of the wastewater. The concentrated light inactivates microbial cells and prevents them from reproducing. The process takes place in an opaque tube in order to protect operators from exposure. The effectiveness of a UV disinfection system depends on the characteristics of the wastewater, the intensity of UV radiation, the time the microorganisms are exposed to the radiation, and the reactor configuration. Some simplified UV tubes have been developed for household-level use. As this disinfection process is purely physical, it provides an interesting alternative where by-products from chlorination are a concern.

REUSE POTENTIAL

- Effluent fit for nonrestrictive irrigation.





UV light module

PROJECT

- **Connected population**: (Cluster of houses) or (Town)
- **Power supply:** Requires a constant electricity supply.

DESIGN

- UV disinfection equipment requires less space than other methods.

OPERATION

- UV disinfection is a physical process rather than a chemical disinfectant; thus eliminating the need to generate, handle, transport, or store toxic/hazardous or corrosive chemicals.
- Low dosages may not effectively inactivate some biological organisms.
- Organisms can sometimes repair and reverse the destructive effects of UV.
- Turbidity and total suspended solids (TSS) in the wastewater can render UV disinfection ineffective.
- Inadequate cleaning is one of the most common causes of a UV system's ineffectiveness.
- Lamps need to be replaced every 6–12 months.

TECH SHEET #18

Disinfection with Chlorine (Cl)

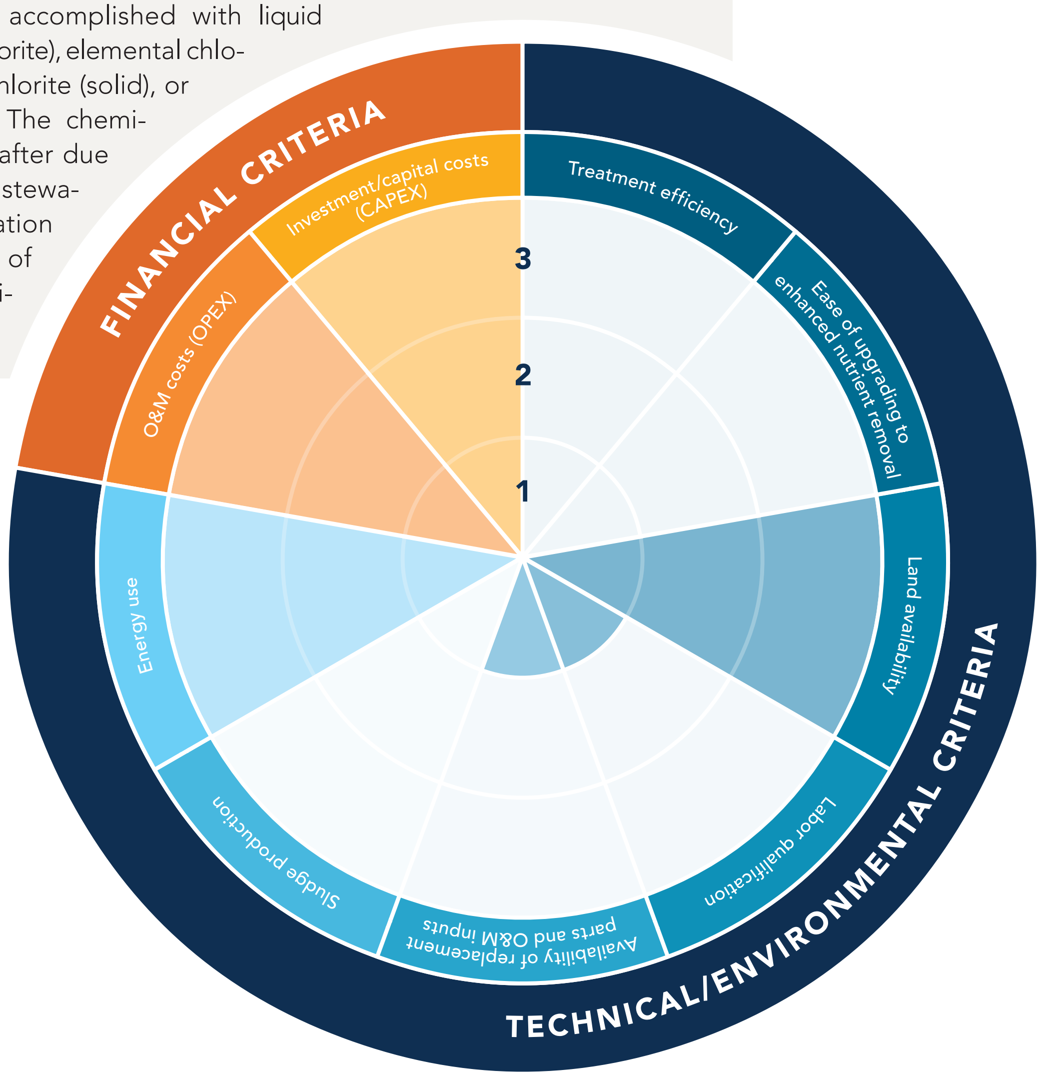
DESCRIPTION

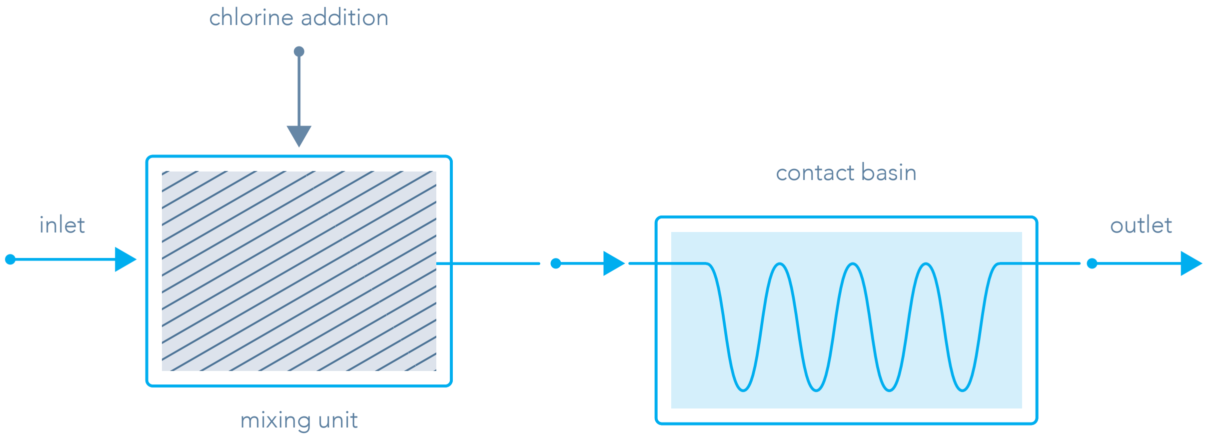
Tertiary treatment, water disinfection
Chlorine kills most bacteria, viruses, and other microorganisms that cause disease. Wastewater and chlorine are first mixed completely and then enter a baffled contact chamber to allow time for disinfection to occur. The radicals formed when the chlorine dissolves in the water 'attack' microorganisms and pathogens by breaking molecular bonds and cells. The effluent is then discharged to the receiving water body or reused, as applicable. The effluent contains residual chlorine, which ensures it is not re-contaminated for a certain amount of time.

Disinfection is usually accomplished with liquid chlorine (sodium hypochlorite), elemental chlorine gas, calcium hypochlorite (solid), or chlorine dioxide (gas). The chemical should be selected after due consideration of wastewater flow rates, application and demand rates, pH of wastewater and chemical availability.

REUSE POTENTIAL

- Effluent fit for nonrestrictive reuse for irrigation.





PROJECT

- **Connected population**:
  (Household),
  (Cluster of houses) or
  (Town)
- Form of chlorine to be used will depend on local availability and connectivity to suppliers.

DESIGN

- Chlorine is a well-established technology, easy to use, solubilize in water and rinse with water.
- Presently, chlorine is more cost-effective than other disinfection methods.

OPERATION

- The chlorine residual that remains in the discharged wastewater can prolong disinfection even after initial treatment and also provides a measure of the effectiveness.
- Chlorine by reacting with certain natural organic compounds creates toxic or ecotoxic by-products. However, the WHO considers that the health risks of these by-products are still low compared to those caused by inadequate disinfection of water.
- All forms of chlorine are highly corrosive and toxic. Thus, storage, shipping, and handling pose safety risks.
- Corrosion or embrittlement of certain plastics and corrosion of many metals (including stainless steel) if the pH of the medium is lower than 8.

TECH SHEET #19

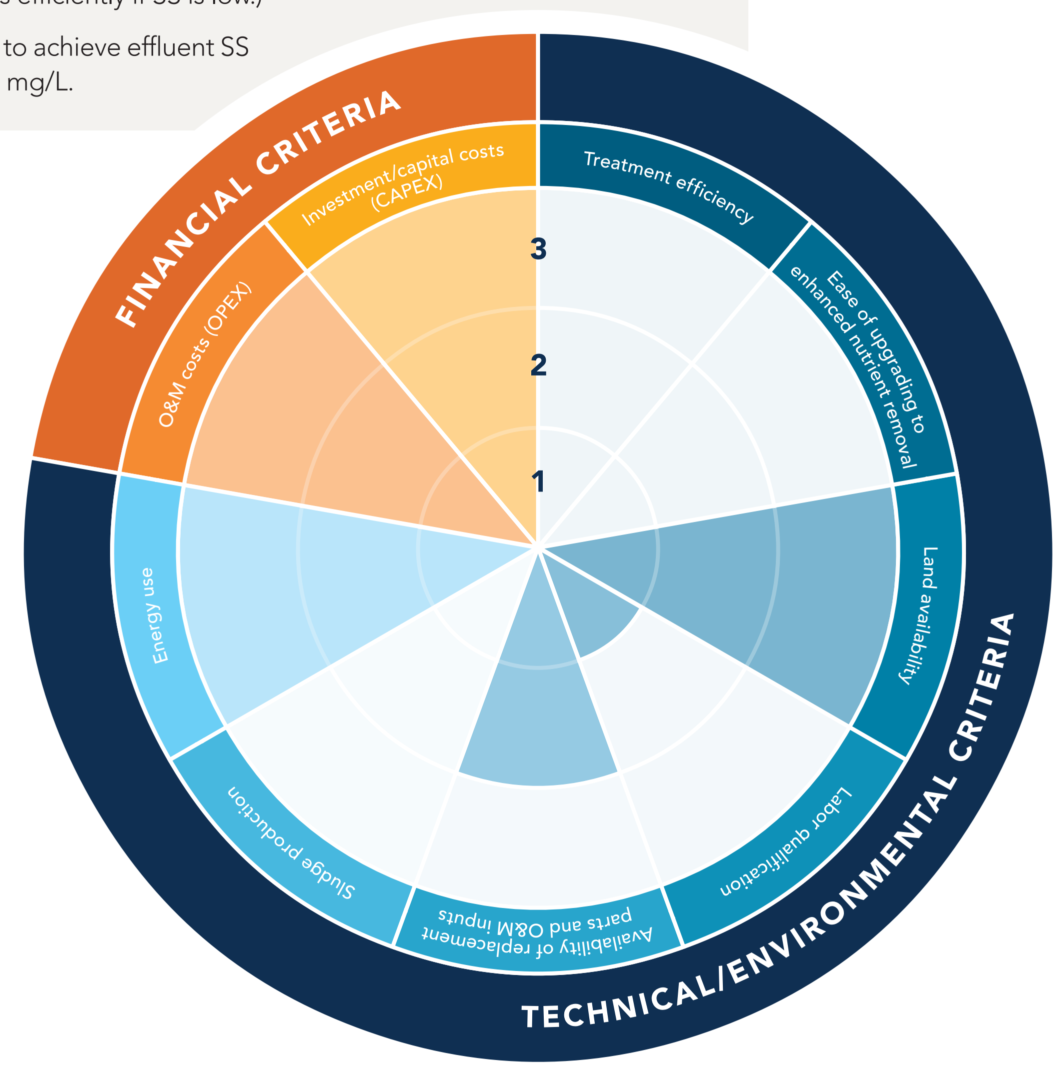
Polishing Pond (PP)

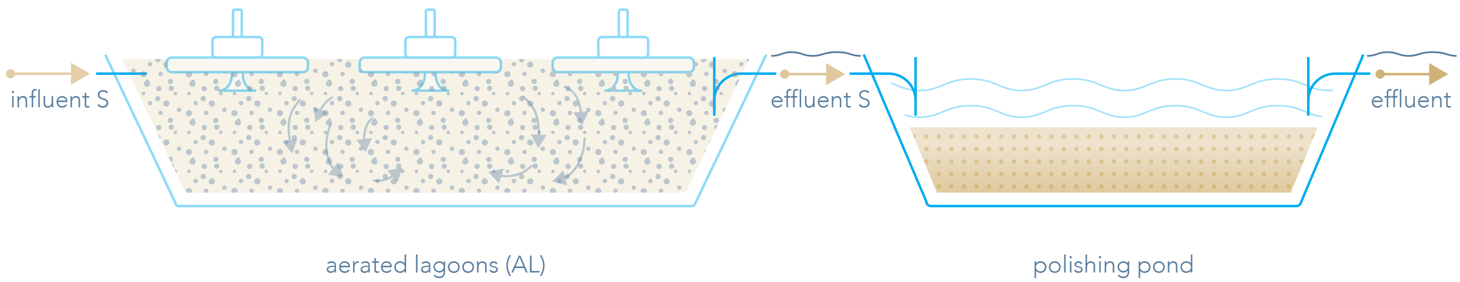
DESCRIPTION

Tertiary treatment for removal of effluent suspended solids (SS)

Polishing Ponds (often also called Sedimentation Ponds) are e.g. employed in the final effluent of Aerated Lagoons, to minimize effluent suspended solids. This is usually done to improve effluent quality as such, since reduced SS also implies reduced BOD_5, COD, TN, TP. Or it may be indirectly necessary to permit UV radiation for disinfection (UV radiation only works efficiently if SS is low.)

Polishing Ponds permit to achieve effluent SS in the range of 20 to 60 mg/L.





PROJECT

- **Connected population:** (Cluster of houses) or (Town)
- **Feasibility of sewerage:** sufficient water supply needed.
- **Regulations for treated discharge & reuse:** dependent on design conditions of prior treatment.
- **Available land:** low-medium footprint.
- **Power supply:** usually not needed.

DESIGN

- Hydraulic retention time in Polishing Ponds should be chosen between 1 to 2 days. To meet this requirement at all times, it is recommended designing for 1 day at design horizon. In order to minimize algae formation, unnecessarily large Polishing Ponds should be avoided.
- Construction of Polishing Ponds follows the principles described in the Technology Sheet on WSPs. Common water depth is 1.5 m.

OPERATION

- Embankments need to be checked regularly and maintained free from large plants; grass needs to be trimmed from time to time.
- In certain intervals sludge removal is required. To that ends it is either necessary to empty the pond first, and then enter with machinery to remove the sludge. Or floating rafts may be employed which have sludge pumps mounted.
- Sludge removal becomes necessary as soon as the sludge is covered by less than 1.0 m water, to minimize odor emissions. Hence with a typical total liquid depth of about 1.5 m in Sedimentation Ponds, the maximum sludge depth is limited to about 33% = 0,5 m.

TECH SHEET #20

Rock Filter (RF)

DESCRIPTION

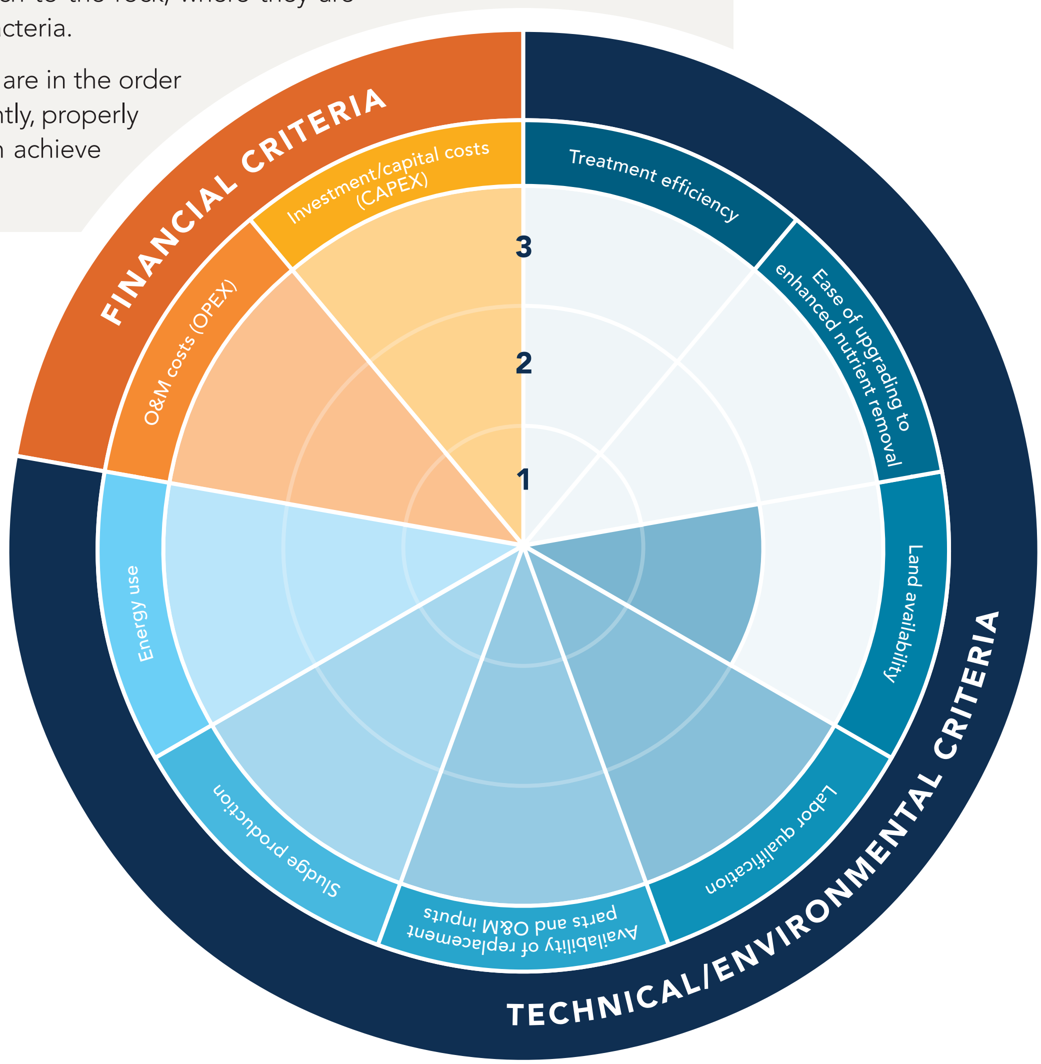
Tertiary treatment for algae removal

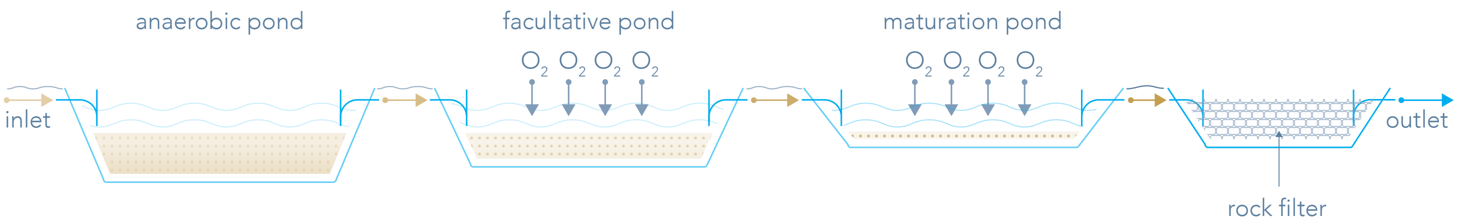
Rock filters provide low-cost, low-maintenance polishing of pond effluents. Their prime effect is removal of algal suspended solids. The system consists of a submerged bed of rocks. Rock filters can be located either in the lagoon / pond effluent zone, or they can be installed as separate units downstream of the lagoon / pond. The algal solids settle and/or attach to the rock, where they are then decomposed by bacteria.

Typical SS removal rates are in the order of 40 to 60%. Consequently, properly designed rock filters can achieve effluent SS of ≤ 30 mg/L.

REUSE POTENTIAL

- Effluent fit for nonrestrictive irrigation.





PROJECT

- **Connected population:** (Cluster of houses) or (Town)
- **Water supply:** sufficient water supply needed.
- **Regulations for treated discharge & reuse:** dependent on design conditions of prior WSP.
- **Available land:** low-medium footprint.
- **Power supply:** usually not needed.

DESIGN

- The design of rock filters usually is done via hydraulic loading rate (HLR). Typical loadings are in the order of 1,0 m^3 effluent/d being applied to 1,0 gross m^3 of rock filter.
- The system consists of a submerged bed of rocks, mostly 75 to 100 (50 to 200) mm in size, with a bed depth of about 1,5–2,0 m, through which the lagoon effluent flows horizontally. The rocks should extend at least 100 mm above the water level, to minimize mosquito breeding and to avoid odor emissions from cyanobacteria that like to develop on wet surfaces exposed to sunlight.

OPERATION

- Optimum cleaning procedures are not clearly established, but periodic removal of accumulated humus may be recommendable.

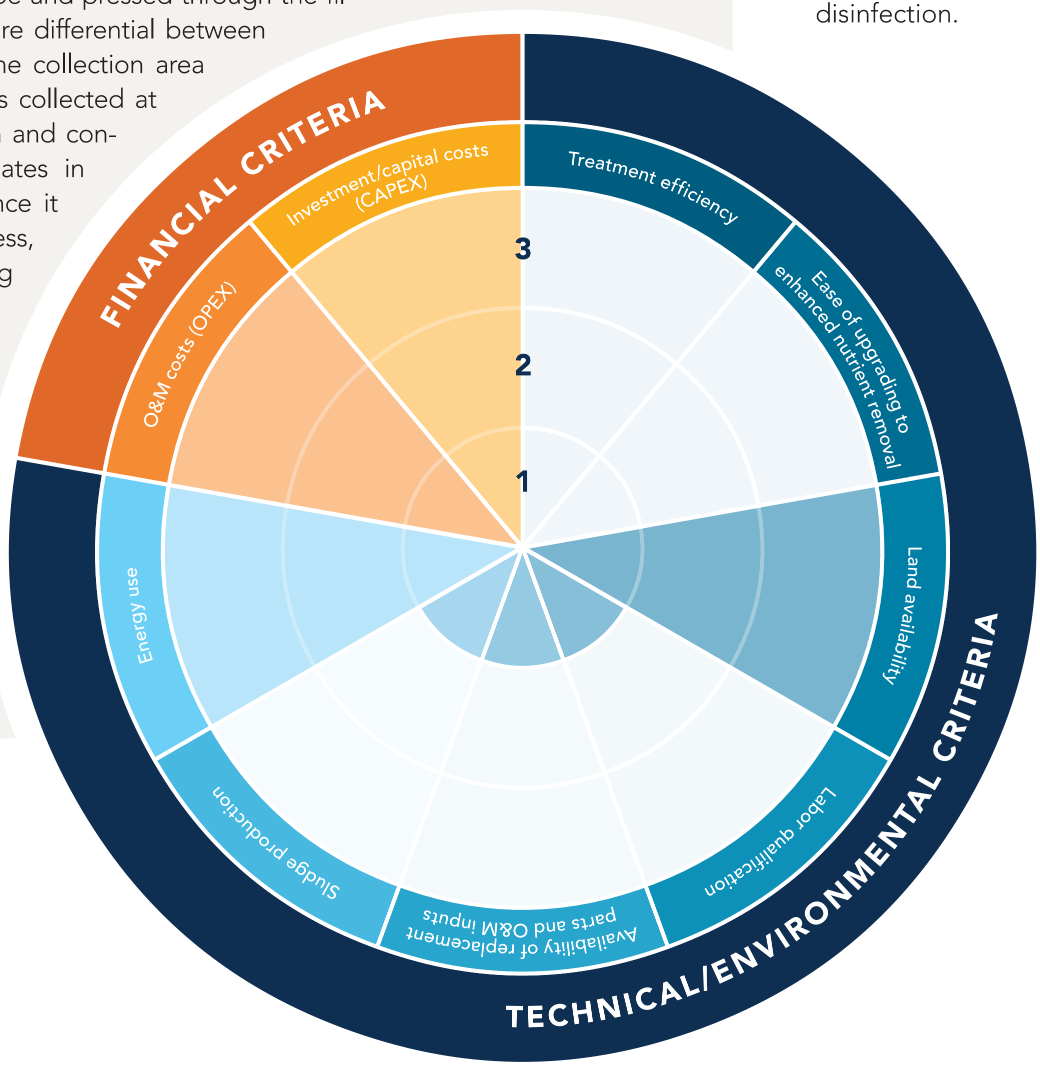
TECH SHEET #21

Rotary Disc Filter (RDF)

DESCRIPTION

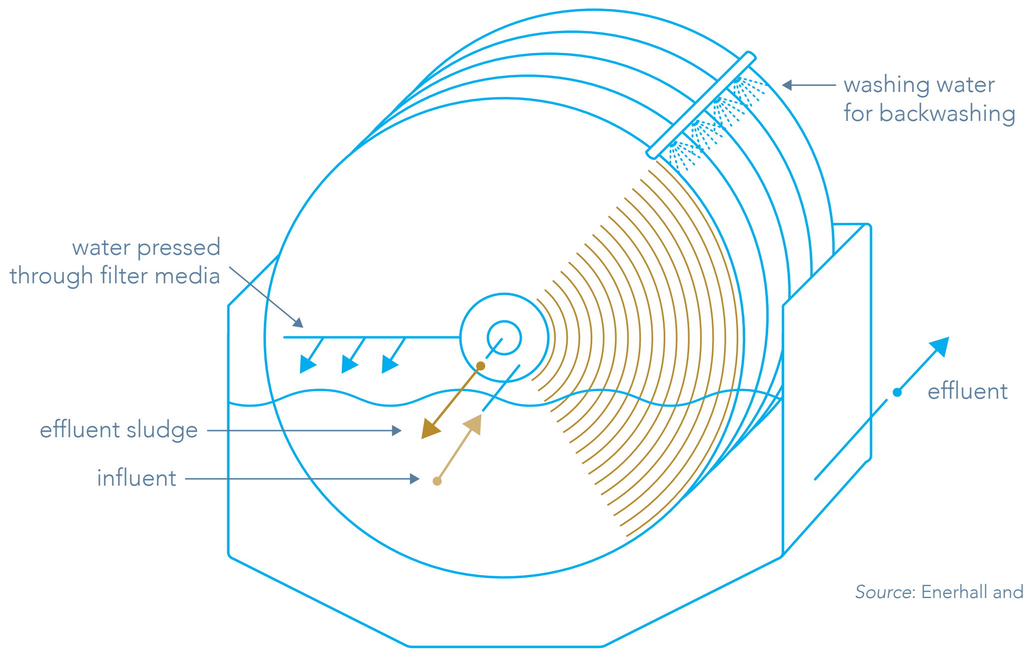
Tertiary treatment

Rotary Disc filters (RDF) are a physical treatment process relying on the filtration of wastewater through disc-shaped filters affixed in a rotating drum to remove residual suspended solids from secondary effluents. The rotating drum is divided into segments, themselves covered with filter media. The wastewater is introduced at the center of the drum through a feed tube and pressed through the filter media by the pressure differential between the filter channel and the collection area outside. Treated water is collected at the bottom of the drum and conveyed. Sludge accumulates in the filter media and, once it reaches a certain thickness, activates the backwashing process which consists in spraying effluent (clean) water on the filter while the drum is rotating, collecting the washwater into a specific pipe for discharge. Filtration can be either constant with continuous backwashing or intermittent.



REUSE POTENTIAL

- Effluent fit for restrictive irrigation.
- Fit for unrestrictive reuse after disinfection.



Source: Enerhall and Stenmark 2012.

PROJECT

- **Connected population:**
  (Cluster of houses)
- No flexibility in changing influent quality. Activities increasing Suspended solids in effluent feeding the ISF are not accepted.

DESIGN

- When using as a tertiary filter, a very fine pore size is required leading to low hydraulic capacity.
- With prefiltration, less energy is required.

OPERATION

- Backwash automatized; backwash filter cleaning every six months.
- Acid cleaning can be used for mineral fouling if needed.

The Optimum Combination of Technologies for Primary and Secondary Treatment

There are many components and treatment stages available, and selecting the optimum combination of technologies—that is, *treatment trains*—can be a challenge. For this reason, this guide also presents several predefined and well-established treatment trains and their main components.

Tables 3.5 and 3.6 present the commonly employed wastewater treatment trains for small-town WWTPs. These draw from the preselected technologies listed in Table 3.4, with Table 3.5 focusing on wastewater and Table 3.6 focusing on sludge treatment. The following points should be taken into account:

- Pretreatment is an indispensable requisite for almost any treatment train, apart from a few stand-alone primary technologies.
- Primary treatment options can be used as stand-alone technologies, albeit with reduced treatment efficiency.
- The most common WWTP technologies are those that employ a combination of primary and secondary treatment elements.
- Tertiary treatment is considered as further improvement after primary and secondary treatment. It is usually not applied after primary treatment.

In addition, Tables 3.5 and 3.6 present components of treatment trains that are typically found in small towns (indicated with black cells), as well as those that are considered to be optional in that they can complement "typical" treatment chains or replace some of their components (indicated with brown cells).

In sludge treatment trains, the most common treatment stages are *thickening* and *dewatering*, both of which serve to reduce the water content in sludge, thereby decreasing the sludge volume. Thickening is the first step of water reduction and is done mostly by gravity. It can also be achieved mechanically on *moving belts* or in *rotating drums*. *Flotation*, which is also a means of thickening, was excluded in the preselection stage because it is not considered financially competitive for small-town WWTPs. Dewatering, the second step in water reduction, is usually done extensively in *drying beds* or intensively in different types of centrifuges or presses, such as *belt filter presses* or *screw presses*.

If sludge is not properly stabilized in the wastewater treatment train—that is, if it continues degrading and emitting bad odors after removal from the treatment train—there is a need for *sludge stabilization*. *Anaerobic digesters* and *aerobic stabilization* are the most commonly used options. UASB reactors can also be used to digest both the primary sludge, which accumulates inside those reactors, and the secondary sludge from the subsequent stages.

Finally, if the dewatering is still insufficient for the disposal or reuse of the sludge, *sludge drying* may also be employed. Possible technologies range from *simple drying beds* to *solar drying greenhouses*. *Thermal driers* are excluded here because they are considered too costly and too operationally demanding for the purpose of small-town WWTPs.

The Optimum Combination of Treatment Technologies for Wastewater Reuse

The challenges of achieving the Sustainable Development Goals (SDGs), combined with water security, have driven countries to identify ways of deriving value from wastewater streams. The potential for wastewater reuse for agricultural, environmental, industrial, residential or municipal uses has consequently become a key factor in WWTP designs. As mentioned in previous chapters,

TABLE 3.5

Typical Wastewater Treatment Trains for Preselected Treatment Technologies for Small-Town WWTPs

#	TECHNOLOGY	ABBREV.	WASTEWATER TREATMENT TRAIN																											
			PRETREATMENT				PRIMARY TREATMENT					SECONDARY TREATMENT														TERTIARY TREATMENT				
			SCREEN	SIEVE	GRIT/FAT REMOVAL	EQUALIZATION	PST	SEPTIC TANK	BIOGAS DIGESTER	IMHOFF TANK	LIQUID/SOLID SEPARATION	ABR	UASB	AT	SBR	STONE MEDIA TF	PLASTIC MEDIA TF	RBC	FST	AERATED LAGOON	ANAEROBIC POND	FACULTATIVE POND	MATURATION POND	ANAEROBIC FILTER	PLANTED GRAVEL FILTER	DISINFECTION–UV	DISINFECTION–CHLORINE	POLISHING POND	ROCK FILTER	ROTARY DISC FILTER
	Primary treatment (only)																													
1	**Septic tank**	ST						■																						
2	**Biogas digester**	BD							■																					
3	**Imhoff tank**	IMH	■		■					■																				
	Primary + secondary treatment																													
4	**Anaerobic baffled reactor**	ABR	■		■							■															▨			
5	**Anaerobic filter**	ANF	■		■			■		▨														■			▨			
6	**Waste stabilization pond**	WSP	■		■																■ (as needed)	■ (as needed)	■ (as needed)				▨		▨	
7	**Aerated lagoon**	AL	■		■															■								▨	▨	
8	**Single-stage constructed wetland**	CW (1-st)	■		■			■		▨		▨													■	▨	▨			
9	**Hybrid constructed wetland**	CW (hybrid)	■	■	■			■		▨		▨													■	▨	▨			
10	**Upflow anaerobic sludge blanket reactor**	UASB	■		■								■														▨	▨		
11	**Extended aeration** (AS type)	EA	■		■									■												▨	▨			
12	**Extended aeration** (SBR type)	SBR (EA)	■		■										■											▨	▨			▨
13	**Trickling filter**	TF	■		■		■			■		▨				▨	■		■							▨	▨			▨
14	**Rotating biological contactor**	RBC	■		■			■		▨		▨						■	■							▨	▨			
15	**UASB-WSP**	UASB-WSP	■	■	■																	■ (as needed)	■ (as needed)				▨		▨	
16	**UASB-TF**	UASB-TF	■	■	■											▨	■		■							▨	▨			

■ Typical component

▨ Optional component (either additional or replacing another component)

Note: The term *waste stabilization pond (WSP)* refers to the classical configuration consisting of anaerobic, facultative and maturation ponds. The term *polishing pond* is used for an optional component to complement technologies and treatment trains, whereas the term *maturation pond* is strictly used as part of WSP systems in this guide. AT = aeration tank; FST = final sedimentation tank; PST = primary sedimentation tank; UV = ultraviolet; WWTP = wastewater treatment plant.

TABLE 3.6

Typical Sludge Treatment Trains for Preselected Treatment Technologies for Small-Town WWTPs

#	TECHNOLOGY	ABBREV.	SLUDGE TREATMENT TRAIN													
			UASB	SEDIMENTATION TANK	GRAVITY THICKENER	MECHANICAL THICKENER	ANAEROBIC DIGESTER	AEROBIC STABILIZATION	POST-THICKENER	MECHANICAL DEWATERING	SLUDGE DRYING BED	SOLAR DRYING	WETLAND	COMPOSTING	SEPTAGE TREATMENT	DIRECT REUSE
Primary treatment (only)																
1	**Septic tank**	ST													■	
2	**Biogas digester**	BD														■
3	**Imhoff tank**	IMH														
Primary + secondary treatment																
4	**Anaerobic baffled reactor**	ABR									■			□		
5	**Anaerobic filter**	ANF									■			□		
6	**Waste stabilization pond**	WSP									■			□		
7	**Aerated lagoon**	AL									■			□		
8	**Single-stage constructed wetland**	CW (1-st)									■		□	□		
9	**Hybrid constructed wetland**	CW (hybrid)									■		□	□		
10	**Upflow anaerobic sludge blanket reactor**	UASB	■							■	□			□		
11	**Extended aeration** (AS type)	EA			■	□				■	□	□		□		
12	**Extended aeration** (SBR type)	SBR (EA)			■	□				■	□	□		□		
13	**Trickling filter**	TF			■	□	□	□	■	■	□	□		□		
14	**Rotating biological contactor**	RBC			■	□	□	■	■	□	■			□		
15	**UASB-WSP**	UASB-WSP	■							■	□			□		
16	**UASB-TF**	UASB-TF	■		□	□				■	□			□		

■ Typical component

□ Optional component (either additional or replacing another component)

Note: WWTP = wastewater treatment plant.

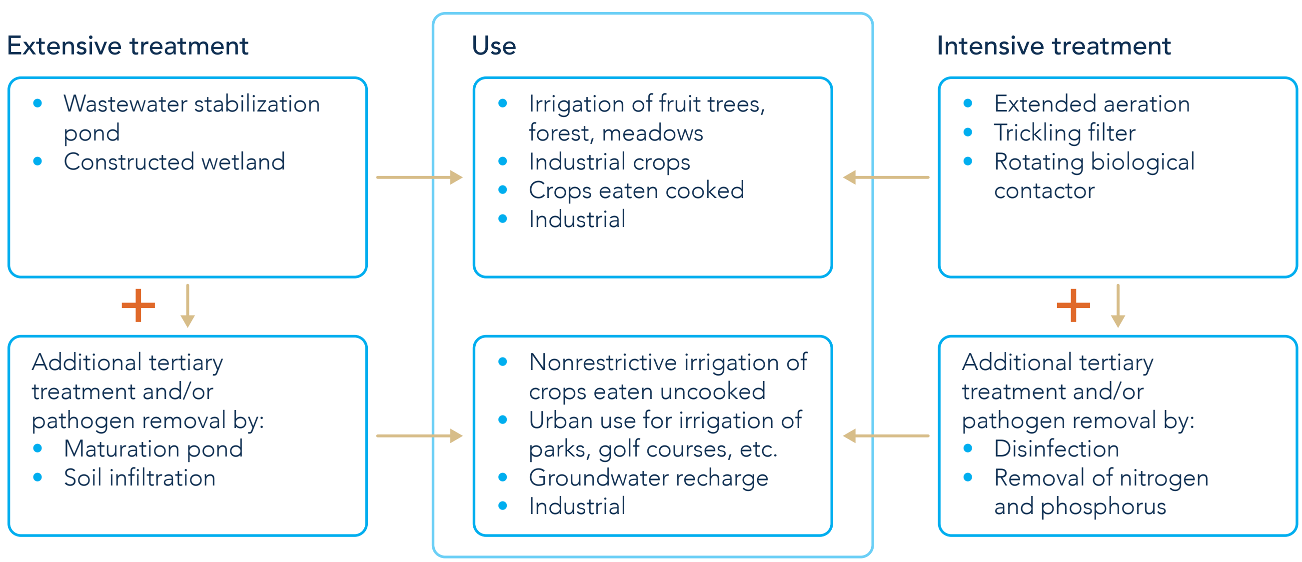
small towns present unique opportunities for reuse in that there is a likely advantage for the treated wastewater to be generated closer to potential reuse sites. This is particularly true for agriculture.

Whereas the primary and secondary technologies presented herein are effective, to varying degrees, at removing suspended solids and organic matter from wastewater, they are generally not sufficient for the removal of pathogenic microorganisms to an acceptable level (WHO 2006). Given the health hazards associated with direct and indirect treated wastewater use, pathogen elimination and monitoring of control measures should be considered an integral part of the wastewater treatment train. Similar to wastewater treatment in general, the optimal combination of technologies to reach a certain level of pathogen removal in a given situation will depend on a variety of factors. Different combinations involving extensive and intensive treatment options can be used to achieve the desired effluent quality levels required for reuse, as shown in Figure 3.1.

The most commonly used indicator parameters to monitor the presence of pathogens in treated wastewater are fecal coliforms (FC) and helminth eggs (particularly intestinal nematode ova), the removal efficiency of which is typically expressed using a logarithmic scale (log units). For example, a reduction in FC concentration from 10^7 FC/100 mL to 10^4 FC/100 mL would correspond to a reduction of 3 log units, or 99.9 percent, as shown in Table 3.7. Furthermore, it should be borne in mind that although 90 percent removal efficiencies may seem high, this represents only a 1 log unit reduction. Much higher pathogen removal rates will generally be required to achieve low effluent concentrations given the high incoming pathogen concentrations in raw sewage, which is particularly the case in LMICs which are often characterized by higher pathogen prevalence in the population and lower overall water usage, with both leading to higher pathogen concentrations in the wastewater. For example, even with a 3-log unit reduction, there would still be 10,000 FC/100 mL left in the effluent, falling short of the required microbial quality to irrigate root crops (unrestricted reuse), according to the 2006 World Health Organization (WHO) guidelines for the safe use of wastewater, excreta and graywater,

FIGURE 3.1

Examples of Combinations of Treatment Options for Different Wastewater Reuse Scenarios



Source: Authors' own work.

TABLE 3.7

Correspondence between Log Units and Removal Efficiency Percentages

PATHOGEN INDICATOR CONCENTRATION IN RAW WASTEWATER (FC/100 mL)	REMOVAL EFFICIENCIES (Log units)	(%)	PATHOGEN INDICATOR CONCENTRATION IN EFFLUENT (FC/100 mL)
10^7	1	90	10^6
10^7	2	99	10^5
10^7	3	99.9	10^4
10^7	4	99.99	10^3
10^7	5	99.999	10^2

Note: FC = fecal coliforms.

and representing a potential public health risk if the treated wastewater were to be reused without further treatment.

Average pathogen removal efficiencies for several technologies and combinations of technologies can be found in the literature, together with information on the removal levels achievable by various control measures aimed at protecting the health of workers and consumers from wastewater pathogens, particularly in the case of treated wastewater reuse for irrigation (Oakley and Mihelcic 2019; WHO 2006). Such protection can be achieved through the establishment of several barriers to contamination, namely: (a) barriers upstream of the reuse perimeter, through the wastewater treatment process itself; (b) barriers at the place of reuse; and (c) barriers at the consumer and household level. For example, although WSPs can typically achieve a reduction of 3 to 5 log units, adopting localized (drip) irrigation could provide an additional pathogen reduction of 2 to 4 log units, depending on whether the harvested parts of the crops are in contact with the soil; the cooking of produce can provide additional pathogen reduction of 5 to 6 log units.

In addition, it is important to note that a well-operated treatment plant meeting its *bacterial* effluent requirements with disinfection may not be able to sufficiently reduce effluent concentrations of *viruses*, *helminth eggs* or *protozoa*, such as *Giardia* or *Cryptosporidium*, thus potentially contributing to public health risks if its effluent is discharged to surface waters that are used downstream as drinking water sources, or if the treated wastewater is used for the irrigation of crops. It is therefore critical to also carefully consider the importance of pathogens that may be a local or regional public health concern, such as protozoa and helminths (instead of just focusing on FC, for example) when selecting treatment technologies for reuse.

Box 3.1 provides two examples of agricultural wastewater reuse, where a combination of technologies would need to be selected to achieve certain effluent quality objectives. In both cases, the selection is dictated by the end use of the treated wastewater or the type of crop to be irrigated.

Note

1. Based on a production rate of 100 L wastewater/cap/d. In addition, BOD_5 refers to the five-day biochemical oxygen demand; PE60 refers to the per capita BOD_5 loading produced during 24 hours, or population equivalent (PE), of 60 g BOD_5/cap/d; and MLD refers to million liters per day.

BOX 3.1

Examples of Technology Selection for Agricultural Wastewater Reuse

EXAMPLE 1: **Intensive treatment option to irrigate lettuce crops.** In this case, costs associated with land acquisition are prohibitively high and an intensive treatment combination could be implemented so that investment costs associated with the civil works and the earth works are minimized. As per the 2006 WHO guidelines (and bearing in mind the need to protect the health of workers in wastewater-irrigated fields against excessive risks of viral, bacterial, protozoan and helminth infections), we see that only a 3 to 4 log unit pathogen reduction will be achieved by the wastewater treatment, whereas a conservative total reduction of 7 log units is needed to ensure the safe consumption of wastewater-effluent-irrigated lettuce. Similarly, additional technologies may be required for the effluent to be considered safe in terms of helminth egg concentrations, which should be reduced below or equal to 1 helminth egg/L, as per these same guidelines. The treatment process could thus include:

TREATMENT LEVEL	TECHNOLOGY	PATHOGEN REMOVAL (LOG UNITS)	HELMINTH EGG REMOVAL (LOG UNITS)
Pretreatment	Screening, oil/grease removal	0	0
Primary	Primary sedimentation	< 1	< 1
Secondary	Trickling filters and sedimentation tank	1–2	1–2
Tertiary	Chlorination	2–6	< 1[a]
Tertiary	Disc filters with a mesh size of ≤ 10 μm[b]	< 1	> 3[c,d]

[a] As part of a recent research project, chlorination was found to provide removal efficiencies of up to 20% (< 0.7 log units). Cornel, P., Kneidl, S., Bishop, F., Schmaußer, S., Merkl, A., and Dehnert, M. 2016. "Elimination of Helminth Eggs." Closing event for the EXPOVAL Federal Ministry of Education and Research (BMBF) Joint Project, Essen, Germany, October 5–6.
[b] Disc filters are increasingly being used not only for solids but also for helminth eggs removal.
[c] Cornel, P., Kneidl, S., Bishop, F., Schmaußer, S., Merkl, A., and Dehnert, M. 2016. "Elimination of Helminth Eggs." Closing event for the EXPOVAL Federal Ministry of Education and Research (BMBF) Joint Project, Essen, Germany, October 5–6.
[d] Quinzaños, S., Dahl, C., Strube, R., and Mujeriego, R. 2008. "Helminth Eggs Removal by Microscreening for Water Reclamation and Reuse." *Water Science and Technology* 57 (5): 715–20.

In this example, chlorination is used to reach this high level of pathogen removal, but such tertiary treatment could also be substituted by posttreatment control measures, such as drip irrigation, exposure to the sun, or rinsing and washing of the lettuce at home. In terms of helminth eggs, the efficiency of their removal will depend on the ova content in the influent wastewater, which can vary significantly, particularly in LMICs (Jiménez and Galván 2007). Assuming a high content of helminth eggs, such as 2,000 eggs/L, the proposed treatment process would be able to reach the recommended limit of £ 1 helminth egg/L, but only with the addition of the disc filters.

EXAMPLE 2: **Extensive treatment option to irrigate olive tree plantations.** In this case, the costs associated with land acquisition are not prohibitive, and land is available near the small town. An extensive treatment solution could thus be implemented, and the operation and maintenance costs could be minimized. An additional 2 to 4 log units of pathogen removal can be achieved through the inclusion of a control measure at the place of reuse, and because olive trees are a high-growing crop, drip irrigation should allow the reuse system to reach a removal of an additional 4 log units. The treatment process could thus include:process could thus include:

TREATMENT LEVEL	TECHNOLOGY	PATHOGEN REMOVAL (LOG UNITS)
Pretreatment	Screening, oil/grease removal	0
Primary	Primary sedimentation	< 1
Secondary	Constructed wetland	3–4
Posttreatment control measure	Drip irrigation	2–4

Factors to Address for WWTPs in Small Towns

4

Users of this guide will be directed through the selection of technologies with the help of two categories of criteria: (a) project criteria, which are external to the technologies and define the characteristics and environment of a given small town and which will affect the technology choice; and (b) technology criteria, which include the technology-specific information (for example, technical performance and characteristics) which will ultimately influence decision making. This section describes each criterion, provides examples, as appropriate, and offers guidance on refining them for a specific context.

Project Criteria

Project criteria aim to identify small-town characteristics that will affect technology choice. The guide suggests six core project criteria that outline important characteristics of the small town, which should be considered when selecting a wastewater treatment system. These highlight the importance of several different aspects that decision makers need to take into account relating to population, growth, local activities and existing services and practices.

Feasibility of Sewers

The presence and quality of other urban services in the target small town will affect the selection of wastewater treatment options. The institution responsible for wastewater management will likely need to engage with other urban service providers to ensure alignment of activities and parameters. The most important urban services which have an influence on the feasibility and efficiency of sewer systems are typically water supply, drainage and solid waste management. The density of housing, and the distance between neighboring houses, also has an important impact on the viability of sewered sanitation as compared to on-site sanitation approaches, such as those provided by septic tanks and pit latrines. The denser the housing in the small town in question, the shorter the sewer extensions, and the more viable are sewers from a financial perspective. Some service providers, such as eThekwini Water and Sanitation in South Africa, have used upfront analyses of the capital cost of laying sewers in comparison to the cost of installing properly designed and constructed on-site sanitation alternatives, in order to identify which approach makes the most financial sense to the utility in a given neighborhood.

Water supply:

Water supply is a key factor when assessing the feasibility of sewers. If there is only intermittent water supply, or if households do not have their own water connections, a sewered sanitation solution may not be appropriate, or it may be appropriate only in certain parts of the town. The same also applies if the water supply consumption per capita is very low and/or if the population is using most of the generated wastewater or graywater for irrigation purposes—for example, in private gardens or vegetable allotments—leaving almost no wastewater for discharge into sewers.

Where water consumption is sufficient and regular, not only can it help estimate the volume of wastewater generated by each household with simple assumptions about the wastewater return coefficient, but the consumption volumes are also closely related to wastewater strength, as measured by its five-day biochemical oxygen demand (BOD_5) or chemical oxygen demand (COD). Where water consumption is high, wastewater tends to be weaker/more diluted, whereas in many LMICs where water consumption can be relatively low, wastewater is correspondingly stronger. Knowing whether households also use their water supply for irrigation purposes will help define the return factor, or the portion of water use that is discharged to the sewer as wastewater. Usually, a value of 0.8 is used, but if a larger part of the water is used for irrigation, a factor of 0.6 could be taken. In addition, if roofs are connected to the sewers (even if that is against local regulations), peak wastewater flow values during rainfall events will be correspondingly larger than usual, thereby also affecting wastewater treatment plant (WWTP) process selection and sizing.

Drainage/stormwater management:

If the town uses a combined sewer system (in which wastewater and stormwater are both collected), WWTPs will need to be sized accordingly—and this may affect the associated capital and operational costs of the WWTP. Combined sewer systems also increase the likelihood of overflow events leading to untreated wastewater being directly discharged to the environment, which may be of particular concern in areas where the receiving body is environmentally fragile or where humans may come into direct contact with the receiving body.

Nevertheless, planning for a separate sewer system (in which wastewater and stormwater are conveyed separately) is no guarantee of well-functioning sewers, as there are numerous examples of defunct or poorly maintained stormwater drainage systems that have serious negative impacts on the sewer system. In situations in which the drainage system is not working properly, residents may try to divert stormwater flows to the sewer system, even if this is not allowed, and the sewers may consequently be hydraulically overloaded. This can lead to combined wastewater-stormwater flows being inadvertently discharged at certain points of the sewer network and possibly overwhelming the hydraulic capacity of the WWTP. In addition, drainage systems may be deliberately intercepted and discharged to sewers, and in such cases, the dilute nature of the flows would also need to be duly taken into account when conceptualizing and designing the WWTP.

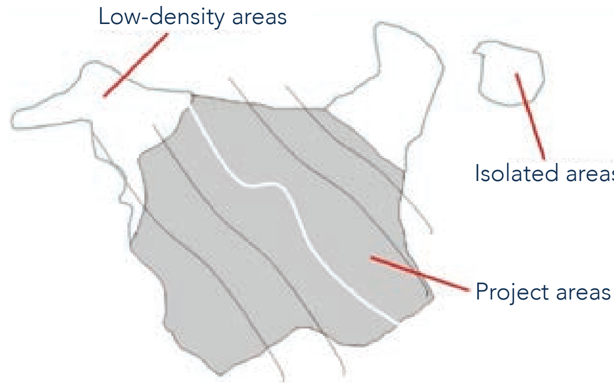
Solid waste management:

If solid waste is not properly managed in the town, excess solid waste may end up in the sewers and at the treatment site. Common implications associated with this include clogged sewer pipes and wastewater pumping stations, emitting bad odors and leading to wastewater spillage, as well as the transmission of the solid waste to the WWTP. Solid waste that arrives at the WWTP can be managed but must be planned for and may require additional steps of pretreatment and operation and maintenance. Ideally, the solid waste should be collected at the source and not allowed to enter the sewers, where it typically requires subsequent elaborate removal efforts.

Total Connections to the WWTP

Total connections to a WWTP are usually expressed in terms of capita (equivalents), reflecting the permanent population and the nonpermanent population, the sewer connection rates, industrial discharges and any fecal sludge that may be disposed of at the WWTP. In addition, the WWTP capacity requirements need to take future growth into account to avoid overloading, and WWTP design horizons are nowadays typically defined on the basis of forecast developments of about 15 to 20 years.

FIGURE 4.1
Defining Project Boundaries



Connected population:

The connected population defines the minimum treatment capacity that needs to be installed for a given wastewater collection system. It should include not only permanent residents but also people passing through or commuting to work in the small town. Such nonpermanent residents are usually multiplied by a factor of 0.3 to 0.5 and then added to the number of permanent residents. The resulting total number is often termed as *population equivalents* or *capita equivalents*, with each capita equivalent representing the typical pollution generated by one permanent resident.

In some cases, only parts of a town will be covered by the sewer system, whereas others will remain with other forms of sanitation services. Political, topographical, urban development and density factors should be considered when defining the sewer project boundaries. Even when a project is meant to cover the whole town, the boundaries between urban and rural areas may not be clearly defined, and decision makers will need to justify whether to include low-density or isolated areas (see Figure 4.1) while ensuring that the project is economically sustainable.

Having a good understanding of the social norms and behavioral characteristics of a relevant sample of the targeted population for the new sewer network can also be beneficial when selecting treatment technologies, particularly as it relates to graywater.[1] The characteristics of graywater depends on several factors, including lifestyle, living standards, social and cultural habits, types and quantities of household chemicals used, food residues, and so on. The biochemical characteristics of graywater can vary greatly, which can influence the selection of wastewater treatment options. For example, in areas where manual laundry washing is common, an increased amount of fiber could make its way to the WWTP, requiring fine screening to improve the pretreatment's efficiency. Graywater can also represent an important part of the total water consumption of a household (and thus of the wastewater flow generated), and an understanding of whether it is discharged into the street, to drains or to sewers will help further guide the selection of wastewater treatment processes for a given small town. Variations in diet can also influence the amount of organic waste produced per person per day (as measured by BOD_5 or COD), and graywater from kitchen sinks can contain elevated amounts of oil and grease, which would require grease traps at the treatment facility. Again, as described earlier, in situations in which not all of the daily wastewater generated by a subgroup of the population is discharged to the sewers (such as that of visitors/commuters), the population equivalent of that subgroup is reduced by a factor reflecting the percentage of pollution that they do, in fact, discharge to the sewers.

Another key aspect related to defining the wastewater flow and treatment capacity of a given system is whether households in the target area end up being actually connected to the sewage network. In many cases around the world, we often see situations in which secondary sewer networks are installed and pass in front of houses but not all households connect to them. This can occur for several reasons including, for example, a lack of financial resources to pay for the connection fee or for the necessary intradomiciliary works, unwillingness to forgo their existing sanitation solution, and/or an inability to bear the cost of sealing a septic tank. Maximizing the connection rate to the sewer network will help service providers and the broader community realize the financial, public health and environmental benefits associated with the investments in sanitation. For more information on how to design and implement sewer connection programs, see the "*Connecting the Unconnected*" guidance document (Kennedy-Walker and others 2020).

Connected industries:

Another source of pollution originates from industrial wastewater flows connected to the municipal sewer system. Estimating the characteristics of these flows can prove difficult, given that industries are often not forthcoming with relevant information and that their water supply schemes may be drawing from private boreholes instead of the public water supply network. These factors notwithstanding, an estimate of the relevant parameters is needed and, ideally, the effluents of major industries should be monitored and analyzed for a period of time in advance of designing the WWTP. If this is not possible, guides on industrial pollution can offer rule-of-thumb values for pollution generated per ton of input processed, per ton of output produced, or per ton of live weight killed for slaughterhouses, and so on. Pollution reduction by pretreatment of industrial effluents should also be taken into account where such facilities exist. The outcome of this exercise then needs to be converted into capita equivalents, either through flow- or pollution-specific per-capita assumptions (for instance, based on 100 liters/cap/d or 50 g BOD_5/cap/d). These theoretical capita equivalents should then be added to the connected population equivalents, as described earlier.

Fecal sludge/septage:

Similarly to the case of industrial pollution, fecal sludge/septage discharged to a WWTP also needs to be taken into account when estimating the total capacity requirements for a small-town WWTP. The fecal sludge volumes are most likely to be of minor relevance compared with the volumes originating from the sewer system, but fecal sludge is usually highly concentrated and the pollution load per cubic meter that is sent to treatment facilities could still be rather high. This fecal sludge pollution load should therefore be considered when estimating the total connections to a WWTP and be converted into population equivalents. The volume of fecal sludge/septage produced will depend on several factors, including containment type, groundwater infiltration and emptying frequency. The volume of sludge taken to a WWTP will be influenced by septage tanker sizes, tanker numbers and the tanker working hours. Bearing these factors in mind, the following rule-of-thumb estimate can be used to calculate the equivalent load associated with septage discharge: 100 people serviced by septage collection and discharge to a WWTP is equivalent to the load of one person serviced by a sewer system.[2] For more details on the issue of fecal sludge and wastewater cotreatment, see the "Fecal Sludge/Septage" criterion below.

Urban and industrial growth:

When designing WWTPs, it is important to assess current and future changes in the characteristics of a given small town that may affect the treatment system. For example, the nature of the local economy, especially the growth of local industry and/or the likelihood that increased or more diverse industrial activity could move into a certain area, may affect the nature of the wastewater influent and therefore the type of treatment needed. Not unlike any feasibility study of treatment alternatives, investigating the dynamics of a small town in terms of population and industrial growth is thus a critical part of the selection process.

The connected population should include not only the current (permanent and nonpermanent) residents but also an appropriate estimate of the population growth over the life span of the WWTP (i.e., the project horizon). Both vegetative growth and migration from nearby rural areas should be considered. If the population growth rate is already particularly high or estimated to increase in a significant way over the coming years, it may make sense to consider treatment plant options that are modular or that allow for incremental capacity to be added over time as population grows (rather than overdesigning at the onset and then operating with a substantial idle capacity for several years).

In addition, designers and decision makers should always bear in mind that planning for future generations should not come at the detriment of first ensuring that all of the existing population has access to sanitation services.

Fecal Sludge/Septage

Fecal sludge/septage can be treated separately in fecal sludge treatment plants or cotreated at WWTPs. There is a growing body of knowledge, experience and literature available concerning typical characteristics of fecal sludge, and its collection, transport and treatment.[3] However, global practical experience of cotreatment of fecal sludge/septage at WWTPs is mixed, and failures are frequent. Since this guide focuses on wastewater treatment, the following comments refer only to situations in which cotreatment may occur. For the separate treatment of fecal sludge/septage in those situations in which cotreatment is not undertaken, see the bibliography listed in this section.

The main issue associated with cotreatment of fecal sludge is that WWTPs are typically not designed for such cotreatment. Consequently, overloading is frequent because even small volumes of fecal sludge can represent high pollution and solids loads for a small-town WWTP. This can manifest itself at the pretreatment stages, where septage is usually discharged from tankers. Screens are not designed to treat waste with such a high solids content, and the raking installations to remove screenings can be overwhelmed. Likewise, grit removal units often cannot cope with the additional solids, and grit cannot be separated properly from the fecal sludge. This results in a potential domino effect, whereby primary settling tanks and sludge removal units are overloaded with both grit and sludge, in turn overloading the secondary treatment stages and ultimately negatively affecting the final effluent quality. In extraordinary cases, the fecal sludge may even contain toxic substances, and because inlet quality control is often weak or nonexistent in small-town WWTPs, then the whole treatment train can be brought to a standstill, requiring emptying of treatment units and a complete restart of the WWTP processes. Given the nature of fecal sludge, the problems mentioned herein also often come hand-in-hand with the emission of bad odors, leading to even stronger rejection of cotreatment practices, both by WWTP operators and by neighboring residents. It is therefore not surprising that success stories of cotreatment, particularly at small WWTPs in LMICs, are rare. This is not to say that cotreatment is unfeasible. It should, however, be incorporated properly into WWTP design and be managed and monitored carefully.

Consequently, this guide advises the limiting of cotreatment of fecal sludge at small-town WWTPs and the allowance of such practices to take place only if all of the following four conditions are met:

(a) *The disposal of fecal sludge is documented reliably at the WWTP,* including the truck driver's name and the origin of the delivered fecal sludge.

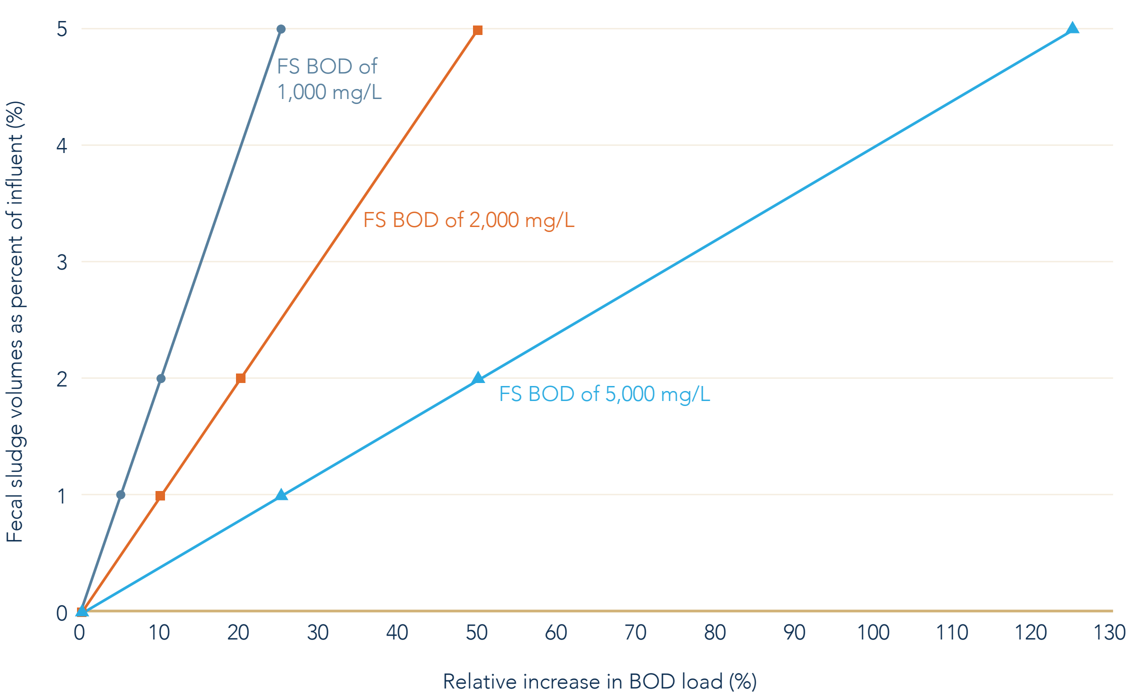
(b) *The accepted daily volume of fecal sludge should not lead to overloading of the WWTP and should be carefully checked.* Although cotreatment may be realistic at large WWTPs with well-trained and qualified personnel, and where the necessary devices for fecal sludge input control are available and properly maintained, small WWTPs usually do not count on these features. Only very small amounts of fecal sludge should, therefore, be accepted. An example of the effects of cotreatment of different fecal sludge volumes on the organic load to be treated at a WWTP is presented in Figure 4.2. For example, whereas a fecal sludge volume representing 2 percent of the total influent discharged to a WWTP can have limited affect on the BOD load at a fecal sludge concentration of 1,000 mg/L (representing a 10 percent increase in the organic loading of the WWTP), a more concentrated fecal sludge of 5,000 mg/L, discharged at this same 2 percent influent volume, could quickly lead to the overloading of the WWTP (as it would represent a 50 percent increase in the organic loading of the plant).

(c) *The fecal sludge has been factored into the WWTP design.*

(d) *The fecal sludge reception station is equipped with a coarse screen and an equalization basin or tank* that has a

FIGURE 4.2

Relative Increase in BOD Load in a WWTP as a Function of the Combined Discharge of Municipal Wastewater and Different Fecal Sludge Volumes



Source: Authors' calculations.
Note: Expressed as a percentage of the total influent discharged to the plant (considering a constant wastewater BOD concentration of 200 mg/L). BOD = biochemical oxygen demand; FS = fecal sludge; WWTP = wastewater treatment plant.

minimum volume equivalent to the volumes of two conventional vacuum trucks used for the collection and transport of fecal sludge.[4] From there, the fecal sludge should then be progressively dosed into the wastewater treatment train.

Regulations for Wastewater Treatment, Effluent, and Sludge Discharge and Reuse

During the design process, stakeholders need to ask themselves several questions regarding the legal and regulatory framework in which a particular project is to be set: "*Are there regulations on wastewater treatment plant design, effluent discharge, sludge management, emissions, and so on?*" "*Is reuse an issue?*" "*If so, what are the existing regulations, and which effluent quality standards are required to be met?*" "*How are the existing regulations enforced, if at all?*" Alternatively, "*are there water quality or environmental standards that would influence reuse, even if these are not specifically geared toward its regulation?*"

In certain cases, there may not be any regulations at all, and stakeholders will need to establish their expectations and derive certain minimum quality standards that the design of the WWTP should meet.

In general, the key parameters that are relevant for WWTP design, and that need to be cross-checked in the available regulations, are BOD_5, COD, suspended solids, nitrogen, phosphorus and fecal contamination indicators, such as fecal coliforms (FC).

Available Land for the WWTP

When initiating the prefeasibility and feasibility phases of the project cycle, it is likely that stakeholders have already identified suitable locations for the planned WWTP. When selecting the location, decision makers should also, to the extent possible:

- Select an area that is not too central and/or surrounded by residential areas, in order to avoid complaints about odor issues, traffic, noise, and so on, but that is also not too distant from the small town to avoid high capital expenditures (CAPEX) associated with pipe procurement and laying and high operating expenditures (OPEX) needed for any pumping required;
- Avoid elevated grounds that would require higher OPEX for pumping;
- Avoid flood-prone areas in order to minimize CAPEX needed for flood protection and to guarantee the WWTP's operational safety. Selecting the location should be based on the best climate change information available and not, for example, only on historical flood data;
- Ensure that the area possesses adequate geotechnical characteristics to sustain the construction of heavy structures and thus minimizes CAPEX for foundation works; and
- Ensure that it offers some reserve areas for potential expansions of the treatment capacity/footprint.

Even if some of the aforementioned criteria cannot be fully adhered to, it is likely that there will be several alternative locations for the WWTP and the maximum available land footprint at those locations will be broadly known. This information will be critical for the comparison of the different technologies available for a given WWTP because, as mentioned earlier, the treatment technologies selected have a direct correlation with their land area requirements.

Power Supply to the WWTP

Before the selection of appropriate technologies, the availability of a reliable power supply to the planned WWTP location will need to be verified, and where it doesn't exist, it should be confirmed whether one can be installed. In addition, certain key characteristics of the available power supply will need to be well understood, such as the maximum possible capacity of that power connection and the duration of power blackouts in the town's power grid. If the power supply were interrupted, for example, flow conveyance could be discontinued, resulting in upstream flooding of pumping stations and an interruption to the normal operation of the downstream wastewater conveyance and treatment facilities. This limitation is typically addressed by providing an emergency power supply, which will add to the CAPEX requirements.

Many wastewater treatment technologies require a continuous external supply of electricity. If electricity is not reliably available in the town, these solutions will likely not be appropriate. Alternatively, other technologies require only medium to low power requirements, or they may not require any power at all. In some cases, the necessary power may even be generated onsite from renewable resources, such as from biogas and/or from photovoltaic modules which, when fully and appropriately assessed, could increase the case of the WWTP not requiring a dedicated energy supply line. In many cases, an unreliable public electricity grid connection may serve only as a backup to a dedicated power line or to an onsite power generation system, when unexpected system failures occur or as a response to peaks in power demand.

Technology Criteria

Technology criteria are considered to be treatment technology-specific, and this guide uses eleven core technology criteria to consider, together with suggested scoring. Chapter 5 (see "How to weight criteria and calculate total scores") provides a summary and an example of the calculation of total scores, based on a set of suggested standard scores and weights.

Treatment Efficiency

When comparing the treatment performance of different technological options, it should be kept in mind that this assessment can be performed through various lenses:

- Removal of organic loads, as measured by BOD_5 and COD
- Removal of pathogens, including viruses, bacteria, protozoa and helminths, as conventionally measured with biological indicator parameters, such as FC and helminth eggs (particularly intestinal nematodes)
- Removal of nutrients, namely nitrogen and phosphorus

Wastewater treatment should result in water quality which is compatible with the sensitivity of the area where the treated effluent will be discharged (i.e., the receiving environment) and which is suitable for any particular reuse application that is envisaged, as well as for the regulatory requirements for both discharge and reuse. If people will come into direct contact with the body of water to which the effluent stream is discharged, pathogen concentrations are typically of greatest concern, whereas in areas where human contact is unlikely, the adverse effect on the receiving water quality of high organic and nutrient concentrations may be the issue deserving the most attention. On some occasions all of these parameters may be of relevance. Ultimately, the technology chosen will need to comply with the discharge standards in effect locally.

When selecting a treatment option, the user should bear in mind that trade-offs between these treatment objectives may need to be made, including between the types of pathogens to be removed. Although "natural" systems, such as lagoons or constructed wetlands, are effective in removing helminth eggs, bacteria, protozoa and viruses, disinfection methods, such as chlorination and ultraviolet (UV) radiation, which are typically coupled with more energy-intensive treatment processes, do not remove helminth eggs as these are very resistant and behave differently from bacteria and viruses during treatment (Jimenez and others 2010). Box 4.1 presents additional considerations when selecting an adequate disinfection method for a small-town WWTP.

It is also important to note that the location of the WWTP could affect the required treatment performance, as plants located closer to urban areas or next to small or sensitive water bodies may require higher efficiency levels, demanding more complex treatment systems and higher investment costs than WWTPs located further from urban areas.

For the purpose of this guide, BOD_5 will be used as the proxy to illustrate and compare the treatment efficiency of different technologies using typical medium-strength raw wastewater (i.e., concentrations of about 300 mg of BOD_5/L). This is considered the key parameter for identifying the content of organic pollution present in raw and treated wastewater, hence it is ideally suited to represent the treatment efficiency in terms of removal of organic pollution. If raw wastewater quality were to deviate strongly from this medium-strength figure, the indicated effluent BOD_5 levels could then go up or down accordingly, but this figure serves as a basis for comparison. To allow an assessment of different categories of achievable effluent qualities, the effluent BOD_5 concentrations are further compared with three arbitrarily defined standards that represent the common range of typical standards found around the world: 20 (strict), 60 (relaxed) and 120 (very relaxed) mg of BOD_5/L.

Figure 4.3 presents minimum, mean and maximum effluent BOD_5 concentrations[5] for a wide range of

BOX 4.1

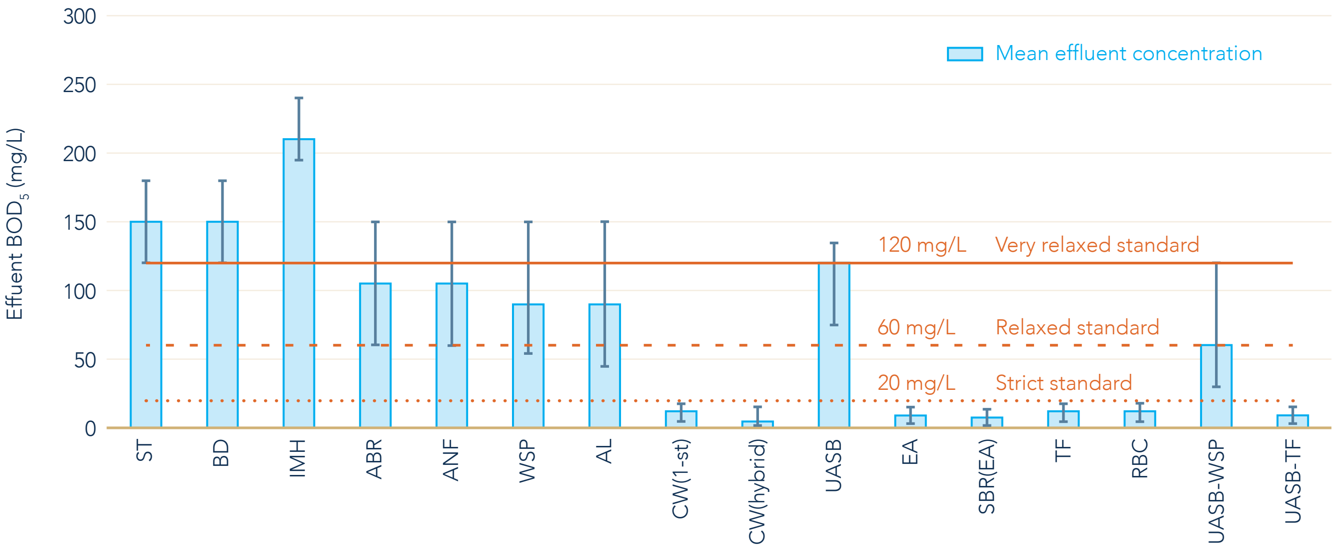
Disinfection Considerations: Formation of Chlorination By-Products

Selecting an adequate disinfection method is an important part of the appropriate disposal and possible reuse of treated effluents, not only in terms of removing potentially pathogenic agents but also in terms of controlling potentially harmful disinfection by-products (DBPs). Disinfection processes can indeed result in the formation of both organic and inorganic DBPs, such as trihalomethane (THM) compounds and haloacetic acids when chlorine is used, and the presence of these compounds is an emerging public health concern to both human health and the aquatic environment, with some compounds having carcinogenic, mutagenic and genotoxic properties ("Science for Environment Policy" 2018). Because chlorination continues to be an important method of disinfecting municipal wastewater—particularly with sodium hypochlorite, which is considered to be a simple and cost-effective process not requiring extensive technical expertise—a prudent course of practice should be pursued to balance the need for removing pathogenic agents and reducing or eliminating the formation of DBPs.

In addition, it has been found that the formation of halogenated organic by-products, such as THMs, is higher in the absence of ammonia and that in WWTPs that do not nitrify, THM formation may not be a problem (Black & Veatch Corporation 2010; Rebhun, Heller-Grossman, and Manka 1997). Since the design and operating conditions associated with small-town WWTPs are unlikely to be favorable to nitrification, THM formation is likely to be minimized in such settings. Chlorination can thus remain an acceptable disinfection option for small-town WWTPs without nitrification. Nevertheless, operating conditions observed in underloaded WWTPs may still lead to nitrification and, notwithstanding the aforementioned consideration, the THM issue may arise in such circumstances. It is therefore important to reliably forecast sewer connection rates (see "Feasibility of Sewers" in Chapter 4) when selecting the optimum disinfection technology for a small town.

FIGURE 4.3

Summary of BOD_5 Effluent Quality Ranges of Different Wastewater Treatment Technologies for Medium-Strength Wastewater



Source: Data collected for this guide.

Note: ABR = anaerobic baffled reactor; AL = aerated lagoon; ANF = anaerobic filter; BD = biogas digester; BOD_5 = five-day biological oxygen demand; CW(1-st) = one-stage constructed wetland; CW(hybrid) = hybrid constructed wetland; EA = extended aeration; IMH = Imhoff tank; RBC = rotating biological contactor; SBR(EA) = sequencing batch reactor (extended aeration variant); ST = septic tank; TF = trickling filter; UASB = upflow anaerobic sludge blanket reactor; UASB-TF = UASB followed by a TF; UASB-WSP = UASB followed by a WSP; WSP = waste stabilization pond.

technologies to help the user make some preliminary comparisons between the available options. The following key conclusions and recommendations can be drawn in terms of treatment efficiency:

- It is clear that primary treatment options alone (septic tank [ST], biogas digester [BD] and Imhoff tank [IMH]) cannot comply with any of the typical BOD_5 discharge standards. These technologies are thus usually not applicable as stand-alone treatment regimes in situations where discharge standards apply.
- Secondary treatment options, either of anaerobic type or those involving ponds (anaerobic baffled reactor [ABR], anaerobic filter [ANF], waste stabilization pond [WSP], aerated lagoon [AL], upflow anaerobic sludge blanket reactor [UASB], UASB-WSP), can only rarely meet typical strict or relaxed BOD_5 discharge standards. Depending on the specifics of a particular project, such technologies could thus be eliminated or require being complemented with tertiary treatment. Examples of complementary tertiary treatment units include:
  - *Rock filters,* which are typically used as tertiary treatment after ponds (WSP, UASB-WSP and AL), including to remove algae from the effluent, and can help bring total suspended solids (TSS) and BOD_5 levels down to about 30 mg/L, if properly designed and operated; and
  - *Polishing or sedimentation ponds,* which are typically used as tertiary treatment after AL and can help bring TSS and BOD_5 levels down to about 20 mg/L, if properly designed and operated. Polishing or sedimentation ponds are characterized by shorter retention times than maturation ponds—usually less than one day—and operate under conditions that allow for some algae to settle and for algal biomass production to be minimized or eliminated, leading to improved effluent parameters.

- In addition, ANF and UASB are rarely used with tertiary treatment, as these technologies are most often followed by another secondary treatment stage, leading to treatment trains, such as the ones included in Figure 4.2, namely UASB-WSP or UASB-trickling filter [TF].
- Several types of secondary treatment, such as single-stage constructed wetland (CW(1-st)), hybrid constructed wetland (CW(hybrid)), extended aeration (EA), sequencing batch reactor (extended aeration variant) (SBR(EA)), TF, rotating biological contactor (RBC) and UASB-TF, can meet strict BOD_5 discharge standards directly, without tertiary treatment.

With this in mind, scores for treatment efficiency are presented in Table 4.1.

In most cases, effluent discharge standards are often already prescribed by the local legislation, particularly for BOD_5, TSS and pathogens (although they may be less so for nutrients), and designers and decision makers will use these effluent quality standards as a starting point to plan for wastewater treatment investments. However, the story can be quite different when it comes to, for example, reuse for irrigation, in which case designers may have to decide the extent to which the targeted effluent quality must go beyond the discharge regulation. In that sense, and in addition to respecting local discharge regulations, designers and decision makers may consider the scenarios presented in Table 4.2, in which treatment performance is linked to the final destination of the effluent to be discharged.

In terms of pathogen removal, the majority of the technologies presented in Figure 4.3 cannot meet typical standards for indicators of pathogens in wastewater effluent, which are typically defined as FC $<$ 1,000 to 10,000 MPN/100 mL, where MPN is the "most probable number," and as $\leq$ 1 helminth egg/L.[6] Only WSPs, if properly designed and operated, may meet such requirements. However, with appropriate tertiary treatment, such as UV or chlorination and filtration, all technologies would be able to meet these pathogen standards.

It remains to be said that fecal sludge treatment plants (typically using WSPs or CWs) can also meet standards similar to what has been described above. Nevertheless, and as mentioned in Chapter 1, this guide focuses on wastewater treatment. For further information on fecal sludge treatment plant technologies, see the sources indicated in "Fecal Sludge/Septage."

Ease of Upgrading to Enhanced Nutrient Removal

Both primary and secondary treatment technologies remove nutrients from wastewater, in particular nitrogen and phosphorus. The typical removal mechanisms involved are sedimentation, adsorption,

TABLE 4.1

Summary of Treatment Efficiency Scores for Different Effluent Concentrations

RELATIVE TREATMENT EFFICIENCY	SCORE	EFFLUENT CONCENTRATION	TECHNOLOGIES
Very relaxed	1	120 mg BOD_5/L and higher	Primary treatment only options
Relaxed	2	Between 60 and 120 mg BOD_5/L	ABRs, ANFs, WSPs, ALs and UASBs
Strict	3	Less than 60 mg BOD_5/L	CWs, EA, SBR(EA), TFs, RBCs, and UASB-TF and UASB-WSP

Note: ABR = anaerobic baffled reactor; AL = aerated lagoon; ANF = anaerobic filter; BOD_5 = five-day biochemical oxygen demand; CW = constructed wetland; EA = extended aeration; RBC = rotating biological contactor; SBR(EA) = sequencing batch reactor (extended aeration variant); TF = trickling filter; UASB = upflow anaerobic sludge blanket reactor; UASB-TF = UASB followed by a TF; UASB-WSP = UASB followed by a WSP; WSP = waste stabilization pond.

TABLE 4.2
Examples of Different Scenarios of Required Treatment Performance

SITUATION	TREATMENT OBJECTIVE(S)	EXPLANATION
Effluent to be discharged into a river with a large dilution effect (that is, a dilution factor of 1 in 100, for example)	Removal of organic loads	The focus of treatment can be limited to the removal of coarse solids and settleable organic matter. Primary treatment could thus be sufficient.
Effluent to be reused for irrigation of a tree crop (for example, for olive trees)	Removal of pathogens and organic loads	The focus of treatment can be on the removal of pathogens (to protect workers' health) and organic loads. Natural systems, such as lagoons-WSPs, or other secondary treatment options with disinfection, for example, would be appropriate. In this particular case, nutrient removal could even be considered counterproductive as the nutrients will naturally help crop growth without the need for artificial fertilizers; additional TSS removal could be needed if drip irrigation is to be used (so as not to clog the drippers). In cases in which there exists a risk of eutrophication of surface or coastal waters, or of phosphorus-induced deficiency of micronutrients in soil, for example, technologies that can achieve high nutrient removal rates might be better suited for the situation, provided that the effluent discharge regulations require nutrient removal.
Effluent to be discharged in a lake requiring water quality for recreational uses	Removal of pathogens, organic loads and nutrients	Removal of pathogens would be required as the effluent could come into direct contact with people, whereas the removal of organic loads and nutrients would be required to preserve water quality and contribute to curbing the potential for eutrophication. Secondary or tertiary treatment options would be required, depending on their potential for nutrient and pathogen removal and based on the effluent guidelines in place.

Note: TSS = total suspended solids.

and the use of those nutrients as building blocks for microbial growth, although the efficiency of each of these mechanisms, even when combined, is relatively limited, ranging from 10 to 30 percent nutrient removal (see, e.g., Metcalf & Aecom 2014).

This is why, when employing technologies that are able to provide nutrient removal rates that go beyond this conventional range, the terms *enhanced nutrient removal* or *biological nutrient removal* (BNR) are used. With such technologies, nitrogen and phosphorus removal efficiencies can climb to 60 to 90 percent or even beyond (Metcalf & Aecom 2014).

When designing a WWTP, effluent standards and the discharge legislation prevailing at that time may not require BNR. However, standards evolve and may eventually become more stringent with regard to nutrients. In such cases, consideration should be given to the ease with which a particular technology can be upgraded to include BNR standards. Bearing this in mind, scores for the ease of upgrading to BNR are presented in Table 4.3.

It is important to highlight that upgrading for enhanced nitrogen removal is generally particularly costly. The CAPEX requirements for such an improvement typically amount to an additional 20 to 30 percent of the original WWTP investment figures. The OPEX of the WWTP will also increase accordingly, as per the higher power requirements associated with increased aeration, return pumping cycles and/or additional mixers. The case for phosphorus is somewhat less costly, but the most common technology used for enhanced phosphorus removal—that is, chemical precipitation—requires the

TABLE 4.3
Summary of Scoring for Ease of Upgrading to BNR and Examples of Scores for Different Scenarios

EASE OF UPGRADING TO BNR	SCORE	TECHNOLOGIES
Difficult – Upgrading to BNR standards is difficult or not possible	1	■ ST ■ BD ■ IMH ■ ABR ■ ANF ■ WSP ■ AL ■ UASB ■ UASB-WSP
Medium – Upgrading to BNR standards is possible, involving medium-level difficulties and medium-level financial resources	2	■ CW(1-st) ■ TF ■ RBC ■ UASB-TF
Easy – Upgrading to BNR standards is technically easy and can be done with relatively limited financial resources	3	■ CW(hybrid) ■ EA ■ SBR(EA)

Note: ABR = anaerobic baffled reactor; AL = aerated lagoon; ANF = anaerobic filter; BD = biogas digester; BNR = biological nutrient removal; CW(1-st) = one-stage constructed wetland; CW(hybrid) = hybrid constructed wetland; EA = extended aeration; IMH = Imhoff tank; RBC = rotating biological contactor; SBR = sequencing batch reactor; ST = septic tank; TF = trickling filter; UASB = upflow anaerobic sludge blanket reactor; UASB-TF = UASB followed by a TF; UASB-WSP = UASB followed by a WSP; WSP = waste stabilization pond.

constant dosage of chemicals, implying an elevated OPEX and a reliable supply of those chemicals.

It is also to be noted that tertiary treatment technologies, which are already considered upgrades and thus are serving a specific purpose, are not considered to be suited for upgrading to BNR—for example, tertiary disinfection does not assist in biological nutrient removal.

Land Availability

As noted earlier, land requirements affect the overall cost of the investment, but land availability, separate from cost constraints, may be a challenge for other reasons. Space requirements can be a limiting factor where population density already constrains new land development, where the space for the treatment plant is already allotted and cannot be expanded, and/or where topography constrains the availability and/or the suitability of sites for certain technologies. Space constraints and proximity to populations may also trigger the need to eliminate certain technologies that can be associated with undesirable odors, for example, and may also require the adoption of treatment systems that are enclosed or that are complemented with adequate odor minimization methodologies or treatment process units. The proximity of the WWTP to urban/residential areas will affect the cost of land (which may also be higher the closer the plant is to the urban center) and may trigger the NIMBY effect.[7]

For the purpose of this guide, relative space requirements are provided for each technology, as specific requirements will be largely dependent on the number of capita (population equivalents) the plant serves and on local conditions (particularly for natural treatment systems).

Table 4.4 presents scores for the relative land requirements of different treatment technologies and examples of the scores allocated for different scenarios of land requirements.

Figure 4.4 presents typical land requirements per capita (population equivalents) for different technologies to help the user make some preliminary comparisons between the available options. Septage treatment plants (SpTPs)[8] using WSPs and CWs are also included here to allow for comparison with the different wastewater treatment technologies.

In addition, the following key conclusions and recommendations can be drawn in terms of land requirements:

- The different treatment technologies presented here show a wide range of land requirements. As a rule of thumb, one may conclude that the

TABLE 4.4

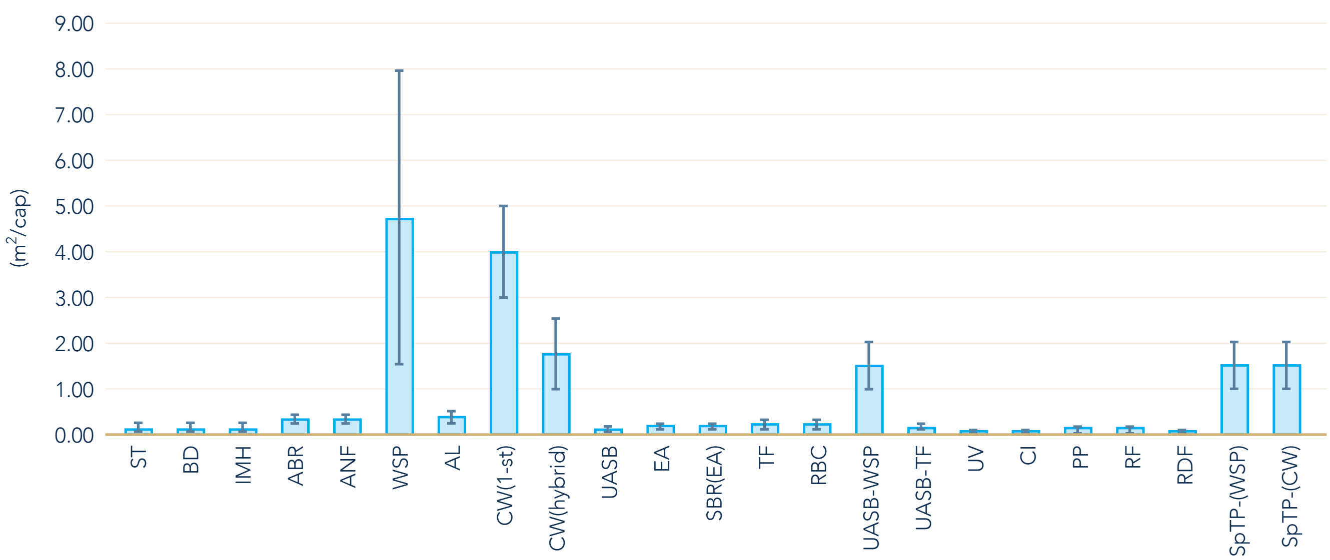
Summary of Scoring for Relative Land Requirements and Corresponding Examples of Scores for Different Scenarios of Land Requirements

RELATIVE LAND REQUIREMENTS	SCORE	TECHNOLOGIES
High	1	■ All types of ponds/lagoons and CWs, including combinations, such as UASB-WSP.
Medium	2	■ Although generally considered to be rather compact processes, UASBs present medium land requirements, particularly because of the need for them to be followed by posttreatment steps, such as TFs or lagoons. ■ PPs and RFs are also associated with medium land requirements.
Low	3	■ Technologies more suitable for clusters of households rather than entire small towns, such as BDs, ANFs and STs, present low land requirements. In addition, these systems and ABRs can typically be built underground. ■ Activated sludge-based technologies and TFs are typically considered to be among the most compact technologies. ■ IMHs, RBCs, RDFs and disinfection by chlorination and UV are also associated with low land requirements.

Note: ABR = anaerobic baffled reactor; ANF = anaerobic filter; BD = biogas digester; CW = constructed wetland; IMH = Imhoff tank; PP = polishing pond; RF = rock filter; RBC = rotating biological contactor; RDF = rotary disc filter; ST = septic tank; TF = trickling filter; UASB = upflow anae robic sludge blanket reactor; UASB-WSP = UASB followed by a WSP; UV = ultraviolet; WSP = waste stabilization pond.

FIGURE 4.4

Summary of Land Requirement Ranges of Different Wastewater Treatment Technologies

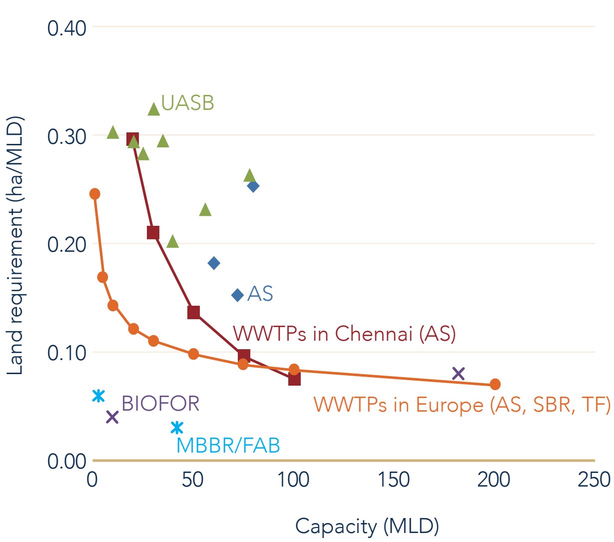


Source: Data collected for this guide.
Note: ABR = anaerobic baffled reactor; AL = aerated lagoon; ANF = anaerobic filter; BD = biogas digester; Cl = chlorination; CW = constructed wetland; CW(1-st) = one-stage constructed wetland; CW(hybrid) = hybrid constructed wetland; EA = extended aeration; IMH = Imhoff tank; RBC = rotating biological contactor; RDF = rotary disc filter; RF = rock filter; SBR(EA) = sequencing batch reactor (extended aeration variant); SpTP = septage treatment plant; ST = septic tank; TF = trickling filter; UASB = upflow anaerobic sludge blanket reactor; UASB-TF = UASB followed by a TF; UASB-WSP = UASB followed by a WSP; UV = ultraviolet; WSP = waste stabilization pond.

easier to a technology is to operate, the more land it requires, and vice versa.

- Three aspects mainly influence the footprint of an individual technology, namely: (a) wastewater temperature; (b) required effluent quality; and (c) economies of scale. In general, if temperature is low, effluent quality standards are strict and/or the WWTP capacity is projected to be small, land requirements are likely to be as indicated by the upper end of the whisker plots shown in Figure 4.4 for each technology. Conversely, if the temperature is high, effluent quality standards are relaxed and/or the WWTP capacity is projected to be high, land requirements are likely to be as indicated by the lower end of the whiskers. As is the case for the other technology criteria listed in this section, the importance of the size of a particular facility is high, as shown in Figure 4.5, which presents the land requirements for different technology trains designed to treat different volumes of wastewater in India and in Europe (ARAconsult 2018).

FIGURE 4.5
Economy of Scale Effect on Land Requirements of WWTPs for Different Wastewater Treatment Technologies



Note: AS = activated sludge; BIOFOR® = biological aerated filter; MBBR/FAB = moving bed biological reactor/fluidized aerated bed; MLD = million liters per day; SBR = sequencing batch reactor; TF = trickling filter; UASB = upflow anaerobic sludge blanket reactor; WWTP = wastewater treatment plant.

Labor Qualification

The level of complexity of the O&M tasks associated with a given treatment system has implications on the required labor force's qualifications to perform these tasks. The existence or absence of this kind of support is an important factor in selecting a treatment process. The qualifications and technical knowledge level of the local workforce may need to be assessed, weighing the demands of each treatment alternative against the effective capacity of the entity responsible for meeting them. The institutional arrangements for running the WWTP will also influence the ease of access of staff with the necessary qualifications. A small town that is disconnected from an urban hub, for example, might not be able to ensure the presence of trained or skilled personnel onsite at all times to operate a UASB system. Alternatively, a regional utility could decide to assign one operator to supervise the O&M of several isolated treatment plants using simpler technology, such as anaerobic and facultative lagoons, which typically require a lower skill set and presence.

This labor qualification criterion, therefore, incorporates two dimensions:

- *Required qualification level for O&M* — that is, skilled labor (trained or specialized technician with minimum background in wastewater treatment or an equivalent field) or unskilled labor (someone who does not require any prior training or certification to perform the required task)
- *Frequency of the O&M tasks* — in particular, whether a permanent presence is required onsite because of the complexity of the tasks or because of the need to perform frequent analyses, which can inform treatment plant operation, for example

Since all technologies require a certain number of unskilled laborers to be on site at least temporarily, this criterion focuses on the type and frequency of required skilled labor inputs. Certain technologies may also require only unskilled and periodic support, such as in the case of ABRs, which require very limited attention to operation and for which maintenance is generally limited to periodic inspections and the removal of accumulated sludge and scum.

With this in mind, Table 4.5 presents the scoring of O&M labor requirements and examples of scores for different scenarios of O&M labor needs.

In addition to considering technical capacity, it may be appropriate and necessary to evaluate human resource capacity for administrative and financial management tasks. A treatment plant demands technical expertise and a minimal institutional and administrative capacity. Keeping a treatment plant in adequate condition requires not only a qualified team of professionals but also an administrative support structure to provide a regular supply of consumables and spare parts. Similarly, the system/engineering design should ensure that the expected O&M costs of the treatment plant being proposed remain within budget and/or within the income-generating potential of the intervention—such a costing analysis should be undertaken in coordination with a financial specialist.

Availability of Replacement Parts and O&M Inputs

Service providers in small towns with limited connectivity to urban or industrial centers, or that host a limited range of economic activities, may lack resources to purchase or procure replacement parts for the wastewater treatment system equipment and other necessary inputs for O&M, such as chemicals, inputs for testing, monitoring, and so on.

TABLE 4.5

Summary of Scoring for O&M Labor Needs and Corresponding Examples of Scores for Different Scenarios of O&M Labor Needs

LABOR NEEDS	SCORE	TECHNOLOGIES
Several skilled laborers required on site	1	■ EA, SBRs, ALs and UASBs typically require several permanent skilled laborers to operate the system, monitor and adjust operation, as needed, and maintain and repair equipment. Smaller UASB systems may only require one skilled laborer onsite, but because UASBs tend to be followed by posttreatment (WSPs or TFs, for example), there may be the need for additional personnel, even in those cases. ■ UV, chlorination and RDFs are also associated with higher levels of training and skill.
One skilled laborer required on site	2	■ TFs typically require one skilled laborer to monitor the filter, regularly clean and maintain the rotary distribution system and repair pumps, as needed. ■ Small RBCs typically require one onsite skilled laborer, with the support of various unskilled or semiskilled personnel for the various maintenance elements, such as replacing seals and motors, servicing bearings and spray-washing discs to clean the attached-growth media.
Periodic support from skilled laborer required	3	■ WSPs mostly require unskilled laborers to remove aquatic plants in the ponds and scum, which may have built up on pond surfaces, and to keep vegetation in check around the banks of the ponds. Periodic support and visual inspection from skilled operators can help adjust operation, maintain treatment efficiency and plan sludge dredging campaigns for the anaerobic ponds, but it is not required daily. ■ All primary treatment options and CWs, PPs and RFs also require only periodic support from skilled laborers.

Note: AL = aerated lagoon; CW = constructed wetland; EA = extended aeration; O&M = operation and maintenance; PP = polishing pond; RBC = rotating biological contactor; RDF = rotary disc filter; RF = rock filter; SBR = sequencing batch reactor; TF = trickling filter; UASB = upflow anaerobic sludge blanket reactor; UV = ultraviolent; WSP = waste stabilization pond.

Alternatively, proximity of the small town to certain suppliers and the reach of the suppliers in a particular country, though advantageous for certain well-established technologies, could complicate access to products needed for undertaking the O&M of other treatment technologies, which are not typically used or are not part of the menu of options currently offered by the local market. When selecting a treatment technology, an assessment of the supply market for these O&M elements would therefore be useful to help characterize the likelihood of providing acceptable treatment performance and compliance at all times for a given option, particularly in environments in which market competition for technological equipment is likely to be limited, as is the case in remote areas with logistical and technical challenges. The same could be said regarding the procurement of technical studies, engineering designs, and construction and supervision services. Consequently, a market study could help identify potential contractors, equipment suppliers and consultants in order to understand their size and limitations and thereby inform and improve procurement planning with regard to civil works and related services, particularly if a decision has been made to expand the menu of available wastewater treatment technological options in small towns.

With these considerations in mind, scores for the availability of replacement parts and O&M inputs are presented in Table 4.6, together with examples for different scenarios.

TABLE 4.6

Summary of Scoring for O&M Inputs and Replacement Parts and Corresponding Examples of Scores for Different Scenarios

O&M INPUTS AND REPLACEMENT PARTS	SCORE	TECHNOLOGIES
O&M inputs and replacement parts are both needed on a regular basis	1	▪ On top of their regular O&M inputs, technologies that include aeration equipment, such as EA, SBRs(EA) and ALs (although ALs typically have simpler aeration equipment than SBRs), will also require readily available replacement parts to prevent extended downtimes that would otherwise result in the creation of anaerobic conditions in the associated reactors. ▪ Tertiary treatment options, such as UV and RDFs, require O&M inputs and replacement parts on a regular basis. For example, the proper O&M of a UV disinfection system includes cleaning of all surfaces between the UV radiation source and the target organisms, as well as the periodic replacement of lamps, quartz sleeves and ballasts. ▪ Systems that require the constant use of chemicals to enhance sedimentation or help with the conditioning of sludge, for example, would also receive a score of 1.
Regular O&M inputs but few replacement parts are needed	2	▪ RBCs, TFs and UASB-TF combinations require few regular O&M inputs, but a readily available supply of seals, motor parts and bearings would be needed. ▪ Chlorination requires regular O&M inputs to clean the various components of the system, as well as needing replacement parts for the chemical dosing pumps and chlorine residual analyzers, for example.
Few regular O&M inputs and replacement parts are needed	3	▪ Primary and secondary treatment options, such as IMH, BDs, STs, ABRs, ANFs, WSPs, CWs and UASBs (and UASB-WSP), require few O&M inputs and few replacement parts. ▪ Tertiary treatment options, such as PPs and RFs, are also assigned a score of 3.

Note: ABR = anaerobic baffled reactor; AL = aerated lagoon; ANF = anaerobic filter; BD = biogas digester; CW = constructed wetland; EA = extended aeration; IMH = Imhoff tank; O&M = operation and maintenance; PP = polishing pond; RBC = rotating biological contactor; RDF = rotary disc filter; RF = rock filter; SBR = sequencing batch reactor; SBR(EA) = sequencing batch reactor (extended aeration variant); ST = septic tank; TF = trickling filter; UASB = upflow anaerobic sludge blanket reactor; UASB-TF = UASB followed by a TF; UASB-WSP = UASB followed by a WSP; UV = ultraviolet; WSP = waste stabilization pond.

Wastewater Sludge Production

Wastewater sludge production and treatment, and the frequency of sludge removal that is required to maintain optimal treatment performance, can together have a significant effect on the O&M costs of a WWTP, such as those associated with sludge dredging, stabilization, conditioning, thickening, dewatering and/or landfilling, as well as on its capital costs by affecting the size of the WWTP's footprint when including sludge drying beds, for example. Sludge handling can represent a particularly important cost for small WWTPs a transport to a municipal landfill site, after dewatering, is often the default solution for small towns unless there is an economically viable land application reuse opportunity for the sludge. Alternatively, depending on the connectivity of the small town with larger agglomerations, sludge from small WWTPs may be transported to larger plants where further sludge treatment could take place, offsetting some of the transport costs with opportunities such as generating biogas at scale at the larger plant. However, it is important to note that in many LMICs, the distances separating small towns from larger urban centers may make such considerations unaffordable.

The amount of sludge production will also be influenced by the existence of a fecal sludge/septage management and treatment system in or near the small town under consideration. If a separate septage treatment facility exists, the WWTP should not be burdened with such additional discharges, but if cotreatment at the WWTP is pursued, it is important to account for the volume and characteristics of the fecal sludge/septage as compared with the wastewater (given the comparatively high strength and high solids content of the former, as discussed early in this guide).

It is important to note that on rare occasions increased sludge production is beneficial—for example, if there is a market for the reuse of the treated sludge. In other situations, where no such market exists and the only approach is to discharge the WWTP sludge to a dumping site, for example, then this criterion will suggest prioritizing a wastewater treatment technology that minimizes sludge production.

With these considerations in mind, scores for sludge production are presented in Table 4.7.

Where a separate wastewater sludge treatment plant/step exists, the complexity of the O&M tasks at the plant can also be considered as a criterion. In other words, even if the sludge removal frequency is low (every two to five years), complex sludge removal and treatment might provide an added burden to the plant's overall O&M. In such cases, the ease of access for removing and transporting the sludge should be considered. For example, difficult access to sludge accumulated in anaerobic or facultative lagoons could either render the dredging process incomplete or costlier, so ease of such maintenance should be incorporated into the design.

It is difficult to pinpoint a precise frequency of desludging that can be associated with a particular technology because it will largely depend on the selected pretreatment and primary treatment steps, as well as on the design, operation and maintenance of the system. For example: an SBR operated in extended aeration mode will require daily sludge removal; a septic tank may require monthly, yearly or even less frequent desludging, depending on the size of the tank; and facultative ponds will need to be dredged once every two to five years, or when the accumulated solids reach approximately one-third of the pond's volume. Nevertheless, the scores presented here are intended to help further guide the user through the selection process by categorizing appropriate technologies according to typical sludge removal needs.

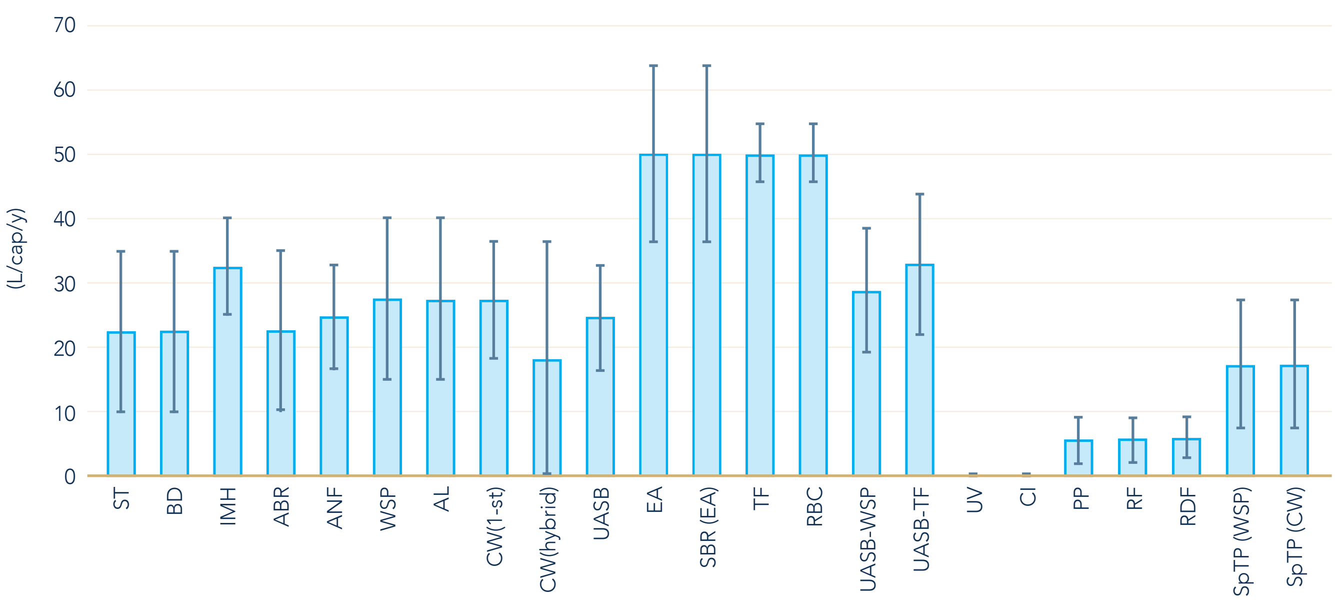
Figure 4.6 presents sludge production ranges for a selection of technologies to help the user compare the available options in a preliminary way. The literature refers to sludge production of different technologies with a wide array of units,

TABLE 4.7
Summary of Scoring for Needed Frequency of Sludge Removal

NEEDED FREQUENCY OF SLUDGE REMOVAL	SCORE	TECHNOLOGIES
Daily	1	■ EA, SBR(EA) and CW(1-st) require daily sludge removal, and TFs (and UASB-TF) and RBCs also require daily handling of the sloughed sludge. ■ Sludge is also removed daily from RDFs, typically with a scraper placed at the top of the filter.
Monthly	2	■ ANFs, CW(hybrid) and UASBs (and UASB-WSP) are associated with a monthly sludge removal frequency.
Every year or more	3	■ All primary treatment options and WSPs, ALs, PPs and RFs require low sludge removal frequencies. ■ For example, anaerobic ponds in WSPs may need desludging every year, whereas facultative and maturation ponds typically require lower frequencies of two to five years and 10 to 20 years, respectively.

Note: AL = aerated lagoon; ANF = anaerobic filter; CW(1-st) = one-stage constructed wetland; CW(hybrid) = hybrid constructed wetland; EA = extended aeration; PP = polishing pond; RBC = rotating biological contactor; RDF = rotary disc filter; RF = rock filter; SBR = sequencing batch reactor; SBR(EA) = sequencing batch reactor (extended aeration variant); TF = trickling filter; UASB = upflow anaerobic sludge blanket reactor; UASB-TF = UASB followed by a TF; UASB-WSP = UASB followed by a WSP; WSP = waste stabilization pond.

FIGURE 4.6
Summary of Sludge Production Ranges of Different Wastewater Treatment Technologies (Assuming a Sludge Dry Solids Content of 20 Percent SS)



Source: Data collected for this guide.
Note: ABR = anaerobic baffled reactor; AL = aerated lagoon; ANF = anaerobic filter; BD = biogas digester; Cl = chlorination; CW(1-st) = one-stage constructed wetland; CW(hybrid) = hybrid constructed wetland; EA = extended aeration; IMH = Imhoff tank; PP = polishing pond; RBC = rotating biological contactor; RDF = rotary disc filter; RF = rock filter; SBR(EA) = sequencing batch reactor (extended aeration variant); SpTP = septage treatment plant; SS = suspended solids; ST = septic tank; TF = trickling filter; UASB = upflow anaerobic sludge blanket reactor; UASB-TF = UASB followed by a TF; UASB-WSP = UASB followed by a WSP; UV = ultraviolet; WSP = waste stabilization pond.

including: liters per capita per year (L/cap/y); grams of suspended solids (SS) per capita per day (gSS/cap/d); grams of SS per gram of COD removed; and grams of SS per gram of BOD_5 at the inlet; among others. Understanding these units and using them to compare technologies can quickly become a difficult task for non-specialists. So, in order to facilitate the comparison of the various technologies, sludge production data are presented here in L/cap/y and is based on a sludge dry solids content of 20 percent of SS, a common dewatering result.

A few key conclusions and recommendations can be drawn in terms of sludge production:

- Primary treatment technologies usually produce a typical sludge volume of about 20 to 30 L/cap/y.
- Similar sludge volumes are also produced by several secondary treatment options, even though these produce better effluent quality than primary treatment options. Particularly outstanding for their appealing combination of low sludge production and excellent effluent quality are CWs and UASB-TF (see Figure 4.3 for effluent quality).
- Secondary treatment options based on aerobic treatment only, such as EA, SBR(EA), TF and RBC, have the highest sludge production rates, typically averaging 50 L/cap/y. This is roughly double the sludge production of any other option.
- Tertiary treatment options are associated with either no additional sludge production (such as for UV and chlorine disinfection) or low additional volumes of sludge, in the order of about 5 L/cap/y. It should be noted that that these are additional volumes of sludge that should be added to those of primary and/or secondary sludge volumes as tertiary treatment is never employed as a stand-alone step.
- Fecal sludge/SpTPs typically present the lowest sludge production rates among treatment solutions, although it is important to bear in mind that the full amount of the fecal/pollution material from these systems is generally transported to the treatment site. Part of the fecal load is, in fact, infiltrated from septic tanks into soak pits or similar devices and that from pit latrines infiltrates directly into the surrounding soil, which explains the lower sludge production figures shown in Figure 4.6.

Energy Use

Energy use associated with wastewater treatment depends on a variety of factors, including the location of the WWTP, the treatment process, effluent quality requirements, the experience of its operators, and the age of the plant and its size (in terms of population equivalent or organic or hydraulic loads).[9] For small towns, the size of a plant is a particularly important factor affecting energy consumption, as smaller plants tend to use more energy on a per-unit basis and can present a limited ability to use energy in a more efficient way, as opposed to larger plants.

Electricity costs in water and wastewater utilities typically vary from 5 to 30 percent of a utility's running costs (ESMAP 2012) and have been reported to comprise between 15 and 50 percent of the total operating costs of WWTPs, with higher costs most likely for very small WWTPs because of the implications of economies of scale, lower efficiency of installations, less sophisticated automation and lower staff skills (Vazquez Alvarez and Buchauer 2014).

As energy use can be a large part of the O&M costs of WWTPs, selecting treatment technologies that fit the responsible entity's capacity to cover these costs, and the availability and reliability of the electricity supply, will thus be critical to ensure the sustainability of sanitation services in small towns employing WWTPs. Depending on the reliability of the electricity supply available in the small town in question, this technology criterion could be given more weight, with intermittent or expensive energy supply skewing technology selection toward solutions that do not require continuous supply or that present low-energy consumption. In addition, the distance of the WWTP from the town center may imply higher energy use linked to conveyance of the wastewater (that is, the greater this distance, the greater the piping and the pumping costs). There may also be energy requirements if the flow at the inlet to the WWTP needs to be elevated to provide gravity flow throughout the WWTP or if pumping to an equalization tank or basin is needed, such as in the case of flow-sensitive treatment technologies. Nevertheless, it should be noted that the energy required for the pumping of the wastewater from the small town to the WWTP is generally not considered here because this may or may not be required depending on local conditions; furthermore, this energy requirement will be identical for any of the possible WWTP technologies/treatment trains in such a small town setting.

With these considerations in mind, scores for energy use are presented in Table 4.8, including different scenarios of energy demand.

Figure 4.7 presents electric power requirement ranges for an array of technologies to help the user make some preliminary comparisons between the available options, from which several key conclusions and recommendations can be drawn:

- All primary and tertiary treatment options and SpTPs are associated with very low energy consumption.
- Within the range of secondary treatment options, there are technologies that have low, medium and high energy consumption. Energy consumption is mostly driven by treatment efficiency—that is, a higher energy consumption goes hand in hand with a higher treatment efficiency, and vice versa. However, this is not always necessarily the case, as shown in Table 4.9: CWs and RBCs, for instance, have excellent treatment efficiency but very low energy consumption.

TABLE 4.8

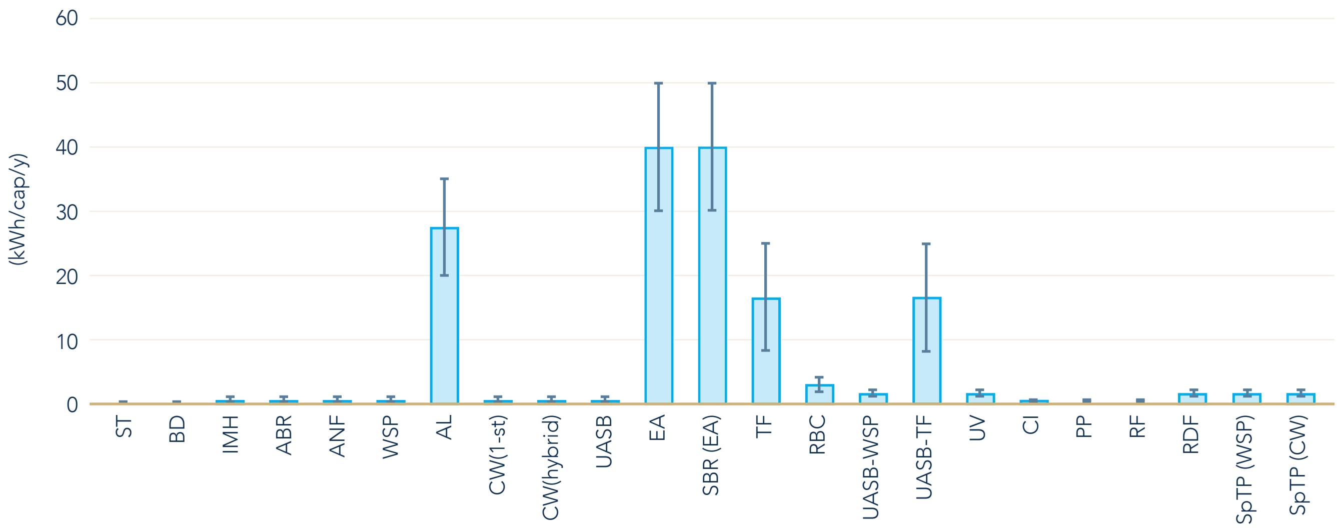
Summary of Scoring for Energy Demand and Examples of Scores for Different Scenarios

ENERGY DEMAND	SCORE	TECHNOLOGIES
Energy required continuously and/or on a set schedule	1	▪ EA variations are associated with high energy consumption as a constant and reliable source of electricity is required to maintain an aerobic environment. They sometimes require aeration to be provided according to a planned schedule; thus, reliability is also critical.
Low to medium energy demand, with energy required non-continuously or on a non-scheduled supply	2	▪ ALs require a reliable source of electricity to maintain an aerobic environment, either in a constant manner or according to a planned schedule. ▪ Although energy demand may be lower than for aerated systems, attached growth systems, such as TFs (and UASB-TF) and RBCs, require a continuous power supply to function properly. For example, TFs require pumping to dose wastewater to the top of the filter, and for recirculation, sludge pumping, digester mixing and centrifuges when these are included in the treatment chain. ▪ Certain types of CWs if pumping is needed for flow distribution.
No energy required	3	▪ WSPs and certain types of CWs do not require energy if gravity is used for the flow between process units. ▪ UASBs consume considerably less energy than aerobic systems but require a constant wastewater flow as these reactors tend to be less robust in the face of organic and hydraulic variability at the inlet. Nevertheless, as upstream pumping energy requirements are not considered here, UASBs are ranked as also consuming negligible amounts of energy. ▪ Primary treatment options, such as ABRs, ANFs, IMH and STs, do not require electrical energy inputs.

Note: ABR = anaerobic baffled reactor; AL = aerated lagoon; ANF = anaerobic filter; CW = constructed wetland; EA = extended aeration; IMH = Imhoff tank; RBC = rotating biological contactor; ST = septic tank; TF = trickling filter; UASB = upflow anaerobic sludge blanket reactor; UASB-TF = UASB followed by a TF; WSP = waste stabilization pond.

FIGURE 4.7

Summary of Electric Power Consumption Ranges of Different Wastewater Treatment Technologies



Source: Data collected for this guide.
Note: ABR = anaerobic baffled reactor; AL = aerated lagoon; ANF = anaerobic filter; BD = biogas digester; Cl = chlorination; CW(1-st) = one-stage constructed wetland; CW(hybrid) = hybrid constructed wetland; EA = extended aeration; IMH = Imhoff tank; PP = polishing pond; RBC = rotating biological contactor; RDF = rotary disc filter; RF = rock filter; SBR(EA) = sequencing batch reactor (extended aeration variant); SpTP = septage treatment plant; ST = septic tank; TF = trickling filter; UASB = upflow anaerobic sludge blanket reactor; UASB-TF = UASB followed by a TF; UASB-WSP = UASB followed by a WSP; UV = ultraviolet; WSP = waste stabilization pond.

TABLE 4.9

Energy Consumption and Treatment Efficiency

	TREATMENT EFFICIENCY		
ENERGY CONSUMPTION	**LOW**	**MEDIUM**	**HIGH**
Low energy consumption	ABR, ANF, WSP, UASB, UASB-WSP	—	CW(1-st), CW(hybrid), RBC
Medium energy consumption	—	AL	TF, UASB-TF
High energy consumption	—	—	EA, SBR(EA)

Note: ABR = anaerobic baffled reactor; AL = aerated lagoon; ANF = anaerobic filter; CW(1-st) = one-stage constructed wetland; CW(hybrid) = hybrid constructed wetland; EA = extended aeration; RBC = rotating biological contactor; SBR(EA) = sequencing batch reactor (extended aeration variant); TF = trickling filter; UASB = upflow anaerobic sludge blanket reactor; UASB-TF = UASB followed by a TF; UASB-WSP = UASB followed by a WSP; WSP = waste stabilization pond.

- Power requirements also depend on the effects of economies of scale, with larger plants consuming less energy per capita of wastewater treated than smaller ones. However, this effect is not as pronounced for energy consumption as it is for land requirements or for OPEX and CAPEX implications.

In addition to energy use, greenhouse gas (GHG) emissions are among the aspects that have become increasingly critical in assessing the overall performance of WWTPs and a deciding factor in technology selection. Wastewater treatment facilities are potential sources of GHG emissions, such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), contributing to climate change and air pollution. CO_2 is also emitted during the production of the energy required for the plant operation, and it can be directly reduced by enhancing energy efficiency at WWTPs, thus creating opportunities to simultaneously reduce environmental effects and treatment costs by seeking to maximize energy savings. For more on the effects of climate change on technology selection, see "Climate Change Impact" in this chapter.

O&M Costs (OPEX)

Figure 4.8 presents OPEX cost ranges for a wide range of technologies to help the user compare the available options in a preliminary manner, keeping in mind that O&M costs can vary based on local markets and other factors.

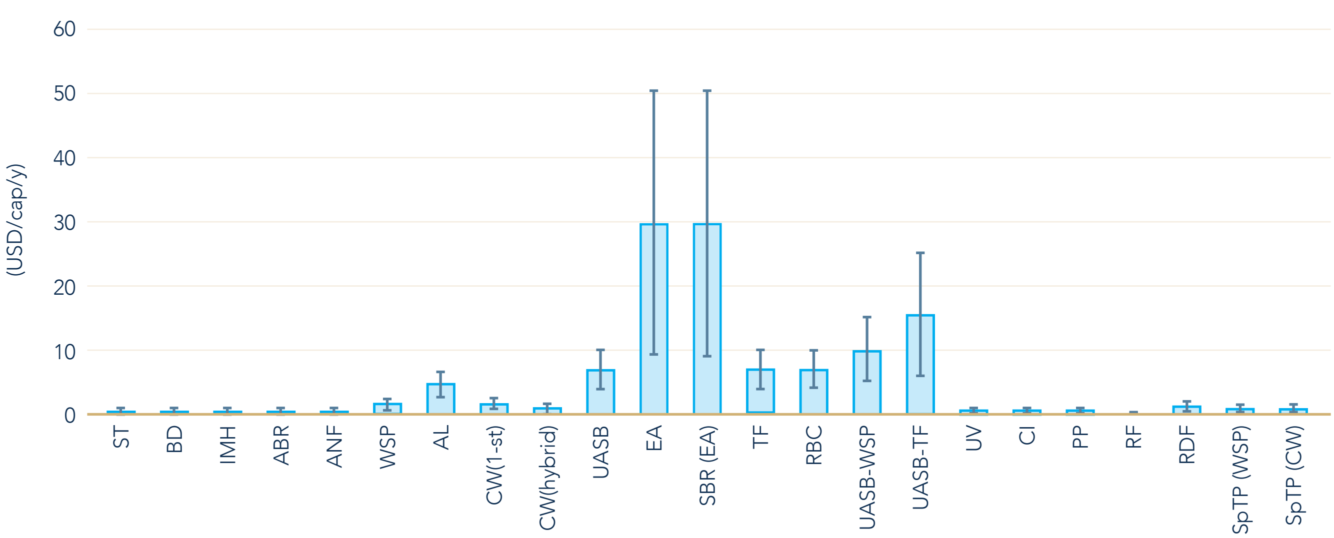
With these considerations in mind, scores for O&M costs (OPEX) are presented in Table 4.10.

A few key conclusions and recommendations can be drawn in terms of OPEX costs, namely:

- Primary treatment usually involves OPEX costs of less than 1 US$/cap/y. OPEX costs associated with SpTPs are also generally at about this level;
- Secondary treatment, depending on the chosen technology and project specific conditions,

FIGURE 4.8

Summary of OPEX Ranges of Different Wastewater Treatment Technologies



Source: Data collected for this guide.

Note: ABR = anaerobic baffled reactor; AL = aerated lagoon; ANF = anaerobic filter; BD = biogas digester; CI = chlorination; CW(1-st) = one-stage constructed wetland; CW(hybrid) = hybrid constructed wetland; EA = extended aeration; IMH = Imhoff tank; OPEX = operating expenditures; PP = polishing pond; RBC = rotating biological contactor; RDF = rotary disc filter; RF = rock filter; SBR(EA) = sequencing batch reactor (extended aeration variant); SpTP = septage treatment plant; ST = septic tank; TF = trickling filter; UASB = upflow anaerobic sludge blanket reactor; UASB-TF = UASB followed by a TF; UASB-WSP = UASB followed by a WSP; UV = ultraviolet; WSP = waste stabilization pond.

TABLE 4.10
Summary of Scoring for O&M Costs (OPEX) and Corresponding Ranges

RELATIVE OPEX RATING	SCORE	COST RANGE	TECHNOLOGIES
High average	1	More than 20 US$/cap/y	EA, SBR(EA)
Medium average	2	3–20 US$/cap/y	ALs, TFs, UASBs (as well as UASB-TF and UASB-WSP), including a nonnegligible part for scum removal, and RBCs
Low average	3	Less than 3 US$/cap/y	Primary treatment alone, tertiary treatment options and ABRs, ANFs, WSPs and CWs

Note: ABR = anaerobic baffled reactor; AL = aerated lagoon; ANF = anaerobic filter; CW = constructed wetland; EA = extended aeration; OPEX = operating expenditures; RBC = rotating biological contactor; SBR(EA) = sequencing batch reactor (extended aeration variant); TF = trickling filter; UASB = upflow anaerobic sludge blanket reactor; UASB-TF = UASB followed by a TF; UASB-WSP = UASB followed by a WSP; WSP = waste stabilization pond.

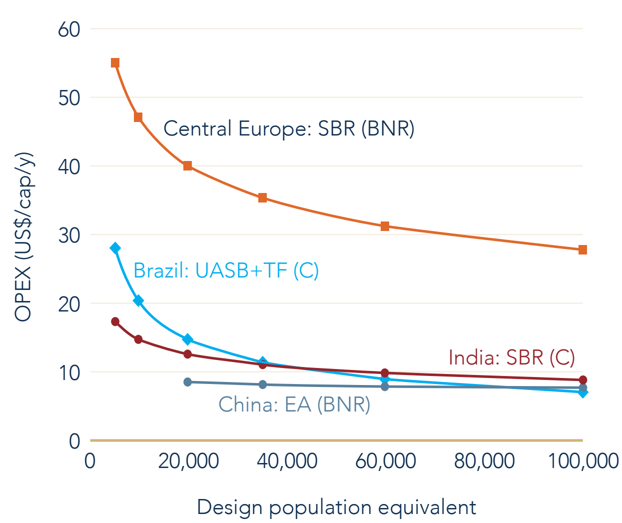
implies OPEX in the range of 0.5 to 50 US$/cap/y. This cost range holds true globally for small-town WWTPs with design sizes ranging from about 5,000 to 100,000 capita. These values may even be higher for very small WWTPs serving less than 5,000 capita;

- A key factor for the estimation of appropriate OPEX of WWTPs is the impact of economies of scale. The smaller a facility, the higher its OPEX per capita are likely to be, and vice versa, which may indicate that the wide ranges of OPEX shown in Figure 4.8 for various treatment solutions are only partially influenced by the locally prevailing unit cost levels. In addition, the design size of a given facility is of major relevance, as illustrated in Figure 4.9, which demonstrates this effect for the OPEX of different technologies. As can be seen from the data collected in different regions/countries, there is generally a unit cost increase by a factor of about two between a WWTP designed for 100,000 capita and a WWTP designed for 5,000 capita. Although this OPEX-related economy of scale effect is not as strong as it is for CAPEX, it is significant enough to be taken into account; and
- Tertiary treatment contributes to a WWTP's total OPEX costs but is usually of relative minor importance when compared with the OPEX costs of the secondary treatment options.

Investment/Capital Costs (CAPEX)

Investment costs include all construction and equipment costs for the treatment processes, including electric and mechanical equipment supply and installation, materials, civil engineering, auxiliary buildings and contractor overheads.

FIGURE 4.9
Economy of Scale Effect on OPEX of WWTPs with Different Wastewater Treatment Technologies and Treatment Standards (2019 Price Level)



Source: Data collected for this guide.
Note: EA (BNR) = extended aeration for biological nutrient removal; OPEX = operating expenditures; SBR (BNR) = sequencing batch reactor designed for biological nutrient removal; SBR (C) = sequencing batch reactor designed for carbon removal only; UASB+TF (C) = upflow anaerobic sludge blanket reactor, followed by a trickling filter, designed for carbon removal only; WWTP = wastewater treatment plant.

Investment costs are typically expressed in local currency units per capita and, when possible, average figures should be drawn from existing in-country experience in installing each process unit, with these figures being reviewed with the local service provider. If no such information is available, costs could then be adapted from experiences in other, comparable, countries using a ratio comparing investment costs in the target country with those in the comparator country for which data are available. The values chosen for this criterion should be defined with the service provider and based on the local market conditions.

For the purpose of this guide, each technology is provided with a relative investment cost rating based on typical experience. Table 4.11 presents the scoring of investment costs and examples of scores for different scenarios of investment costs.

Although the total investment costs should also include the cost of the land needed for the WWTP's footprint, it is treated as a separate criterion in this guide (see "Land Availability"). This will have an effect on the classification of certain technologies with regard to investment costs, particularly waste stabilization ponds/lagoons. All types of WSPs/lagoons can present high investment costs because of their large land requirements depending, of course, on the local price of land. However, because, for the purpose of this guide, the cost dimension of land is incorporated into the land requirements criterion, WSPs/lagoons are scored as technologies with medium investment costs. It should be noted that a WWTP located further from the urban center or residential areas may incur higher investment costs related to the wastewater conveyance infrastructure (piping and pumping) but may result in lower land

TABLE 4.11

Summary of Scoring for Investment Costs and Examples of Scores for Different Scenarios

RELATIVE INVESTMENT COSTS	SCORE	COST RANGE	TECHNOLOGIES
High	1	More than US$ 150 per capita	■ EA and SBR(EA) is generally associated with high investment costs because of the importance of the civil works and the complex equipment needs. ■ The same applies to CWs, RBCs, TFs, UASB-TF and UASB-WSP.
Medium	2	US$ 50–150 per capita	■ Primary treatment options, such as IMH, ANF and all types of lagoons and UASBs, are generally associated with medium investment costs.
Low	3	Less than US$ 50 per capita	■ Technologies more suitable for clusters of households rather than entire small towns, such as BDs and STs, present low investment costs. ■ ABRs are generally associated with low investment costs. ■ Tertiary treatment options, such as PPs, RFs and RDFs, are associated with low investment costs. Disinfection technologies, such as chlorination and UV radiation, when taken on their own, have low investment costs, although they are typically incorporated into a larger treatment chain with higher investment cost implications.

Note: ABR = anaerobic baffled reactor; ANF = anaerobic filter; BD = biogas digester; CW = constructed wetland; EA = extended aeration; IMH = Imhoff tank; PP = polishing pond; RBC = rotating biological contactor; RDF = rotary disc filter; RF = rock filter; SBR(EA) = sequencing batch reactor (extended aeration variant); ST = septic tank; TF = trickling filter; UASB = upflow anaerobic sludge blanket reactor; UASB-TF = UASB followed by a TF; UASB-WSP = UASB followed by a WSP; UV = ultraviolet; WSP = waste stabilization pond.

costs given the increased distance from the small-town center.

It should also be kept in mind that certain technologies included in this guide are meant to be used together as part of a treatment train. In practice, this means that each step of the treatment train would need to be costed to understand the full cost of treatment for different treatment systems (each of which may include several treatment technologies).

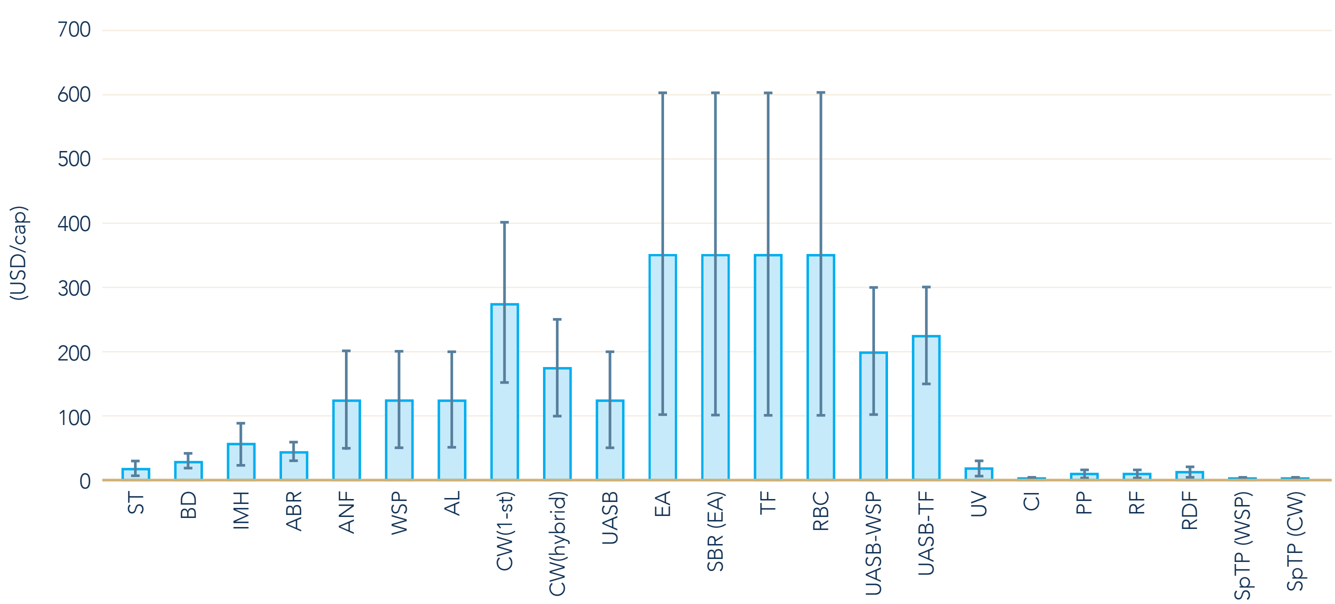
Figure 4.10 presents typical construction costs per capita for different technologies to help the user make some preliminary comparisons between the available options. Nevertheless, it is important to acknowledge that although some technologies may have similar per capita construction costs, certain technologies (for example, septic tanks or sand filters) are more appropriate for individual households or clusters of households and therefore offer limited opportunities for economies of scale. The issue of economies of scale for capital costs is important for trickling filters, lagoons and UASBs, for example, which are typically used for larger small-town population clusters. In addition, the costs presented for individual technologies would need to be added, depending on the treatment train chosen.

A few key conclusions and recommendations can be drawn in terms of CAPEX costs, namely:

- Primary treatment usually corresponds to CAPEX of less than US$ 50 per capita;
- Depending on the technology employed and on project specific conditions, the CAPEX for secondary treatment range from US$ 50 to 600 per capita. This cost range holds true globally for small-town WWTPs with design sizes ranging from about 5,000 to 100,000 capita, and these values could even be higher for very small WWTPs of less than 5,000 capita;
- A key factor for the estimation of appropriate CAPEX of WWTPs is the effect of economies of

FIGURE 4.10

Summary of CAPEX Ranges of Different Wastewater Treatment Technologies



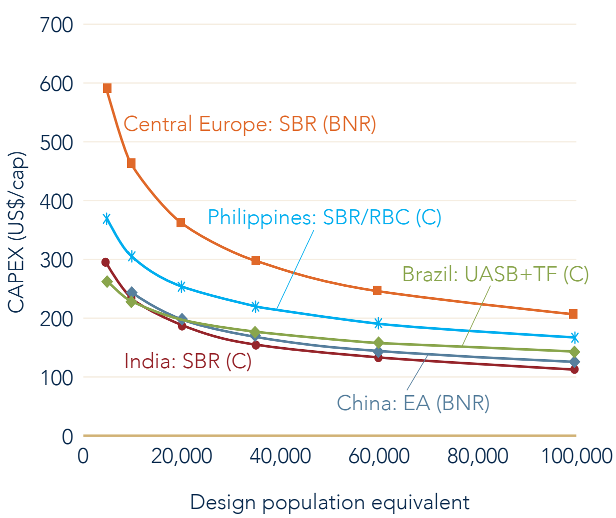
Source: Data collected for this guide.
Note: ABR = anaerobic baffled reactor; AL = aerated lagoon; ANF = anaerobic filter; BD = biogas digester; Cl = chlorination; CW(1-st) = one-stage constructed wetland; CW(hybrid) = hybrid constructed wetland; EA = extended aeration; IMH = Imhoff tank; PP = polishing pond; RBC = rotating biological contactor; RDF = rotary disc filter; RF = rock filter; SBR(EA) = sequencing batch reactor (extended aeration variant); SpTP = septage treatment plant; ST = septic tank; TF = trickling filter; UASB = upflow anaerobic sludge blanket reactor; UASB-TF = UASB followed by a TF; UASB-WSP = UASB followed by a WSP; UV = ultraviolet; WSP = waste stabilization pond.

scale. The smaller a facility, the higher its CAPEX per capita are likely to be, and vice versa, which may indicate that the wide ranges of CAPEX shown in Figure 4.10 for various treatment technologies are only partially influenced by the locally prevailing unit cost levels. In addition, design size of a given facility is of major relevance, as illustrated in Figure 4.11, which demonstrates this effect for CAPEX of different technologies. As can be seen from the data shown from different regions/countries, there is a general unit cost increase by a factor of about 2.5 to 3 when comparing a WWTP designed for 100,000 capita and one designed for 5,000 capita;

- Tertiary treatment contributes to a WWTP's total CAPEX but is usually of relative minor importance when compared with CAPEX costs of secondary treatment options; and
- SpTPs are advantageous in terms of CAPEX, and capital investment figures of such sanitation

FIGURE 4.11

Economy of Scale Effect on CAPEX of WWTPs with Different Wastewater Treatment Trains (2019 Price Level)



Source: Data collected for this guide.
Note: EA (BNR) = extended aeration for biological nutrient removal; OPEX = operating expenditures; SBR (BNR) = sequencing batch reactor designed for biological nutrient removal; SBR (C) = sequencing batch reactor designed for carbon removal only; UASB+TF (C) = upflow anaerobic sludge blanket reactor, followed by a trickling filter, designed for carbon removal only; WWTP = wastewater treatment plant.

systems are further reduced by the fact that no extensive sewer system is required.

The CAPEX and OPEX figures are presented separately here, which could lead to questions concerning the overall least cost solution when combining the CAPEX and the OPEX. To guide the user with regard to this issue, Box 4.2 presents an example of a life-cycle cost analysis and the calculated net present value (NPV) for different wastewater treatment technologies. The outcome offers some useful insights However, given that this analysis is based on the assumptions presented in the box, and since specific project conditions may deviate considerably from these assumptions, the results should be interpreted accordingly.

Reuse Potential

This section discusses which products are generated by a given treatment process and which of these lend themselves to reuse. As mentioned in the "Wastewater Resource Recovery" section of Chapter 2, when selecting an appropriate technology for a small town, the quality of these end products and their potential uses should be matched with existing or potential local demand for the products. This criterion is thus most relevant where there is interest in the reuse of such products. However, keeping this criterion in mind can also be helpful in cases where informal reuse is ongoing and could be formalized, where legislation is in place for such reuse but it is not yet practiced, and/or where decision makers are considering or drafting legislation to enable the reuse of wastewater reuse products.

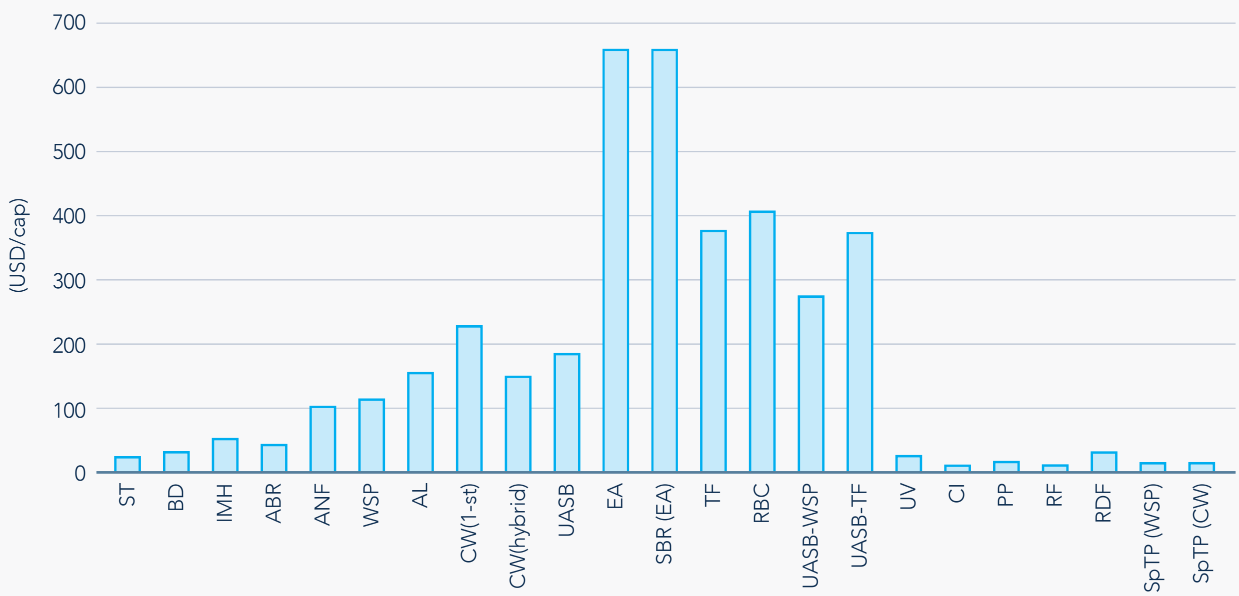
In addition, interrelations between wastewater treatment and the treatment, handling and disposal of the generated wastewater sludge, need to be carefully studied when selecting and designing a treatment option, particularly as sludge disposal or reuse may require a certain sludge quality, which in turn calls for appropriate treatment of the sludges produced along the wastewater treatment chain (Andreoli, Von Sperling, and Fernandes 2007). For

BOX 4.2
Life-Cycle Cost Analysis

The life-cycle cost analysis presented here is based on the following assumptions:

- Capital expenditure (CAPEX) figures are the average values presented in Figure 4.10.
- CAPEX is split into a civil works (CIV) component and a mechanical-electrical (ME) component according to typical percentages.
- Operating expenditure (OPEX) figures are the average values presented in Figure 4.8 and are assumed to be constant over the total calculation period.
- Life span of CIV = 30 years.
- Life span of ME installations = 15 years.
- Discount rate = 4 percent.
- The net present value (NPV) calculation was undertaken for a period of 15 years, with the ME component completely written off by then and with a 50 percent residual value for the CIV component at the end that 15-year period.

FIGURE B4.2.1
NPV Results for Different Wastewater Treatment Technologies



Note: ABR = anaerobic baffled reactor; AL = aerated lagoon; ANF = anaerobic filter; BD = biogas digester; Cl = chlorination; CW(1-st) = one-stage constructed wetland; CW(hybrid) = hybrid constructed wetland; EA = extended aeration; IMH = Imhoff tank; NPV = net present value; PP = polishing pond; RBC = rotating biological contactor; RDF = rotary disc filter; RF = rock filter; SBR(EA) = sequencing batch reactor (extended aeration variant); SpTP = septage treatment plant; ST = septic tank; TF = trickling filter; UASB = upflow anaerobic sludge blanket reactor; UASB-TF = UASB followed by a TF; UASB-WSP = UASB followed by a WSP; UV = ultraviolet; WSP = waste stabilization pond.

(*continues on next page*)

BOX 4.2

Life-Cycle Cost Analysis (*Continued*)

The results show an extremely wide range of NPV values, and the following conclusions can be drawn from this exercise regarding life-cycle costs:

- Intensive secondary treatment technologies, such as extended aeration (EA), trickling filters (TFs) and rotating biological contactors (RBCs), are by far more expensive than extensive technologies, such as waste stabilization ponds (WSPs) and aerated lagoons (ALs), and are more expensive than primary treatment technologies and septage treatment plants (SpTPs). Additionally, tertiary treatment stages, such as disinfection and polishing, do not result in important additional life-cycle costs;
- Within the group of intensive technologies, the two investigated extended aeration variations of the activated sludge process, namely EA and sequencing batch reactor (SBR)(EA), are approximately 50 percent more expensive than other intensive alternatives, such as TF, RBC and upflow anaerobic sludge blanket reactor with ponds (UASB)-WSP and UASB with trickling filters (UASB)-TF;
- Among secondary treatment extensive technologies, WSPs, ALs and hybrid constructed wetlands (CWs) are the most cost-efficient options; and
- When additionally comparing the ability to meet effluent quality standards, in parallel to life-cycle cost considerations, hybrid CWs stand out as a cost-effective solution because this technology delivers an effluent quality comparable to activated sludge systems (see "Treatment Efficiency") but for an NPV of just about 25 percent of that of the EA systems.

example, the following additional sludge treatment steps may be required:

(a) Sludge stabilization is important for most kinds of reuse because it minimizes bad odors emitting from the sludge. Hence, to render sludge attractive for users, this is a common minimum requirement. Stabilization can be achieved by various means: anaerobic digestion, extended aeration or the application of chemicals;

(b) Sludge conditioning, through the addition of chemicals (coagulants and polyelectrolytes) to improve solids capture;

(c) Sludge dewatering, which has an important impact on transport and final destination costs, as well as on ease of sludge handling (if a WWTP is close to agricultural land and sludge quantities are not significant, the dewatering step may be eliminated as the sludge could be applied directly to the land in its liquid form); and

(d) Pathogen removal when agricultural reuse is considered through, for example, lime treatment, composting and/or solar/thermal drying.

The production and use of biogas from the sludge may require additional treatment steps and process units—for example, contaminants in the digester gas that should be reduced for co-generation include moisture, hydrogen sulfide and siloxanes (Kalogo and Monteith 2008; Vazquez Alvarez and Buchauer 2014). In all cases, the selection of a technology for reuse purposes would need to meet the corresponding reuse standards.

Table 4.12 presents a template that can be used to evaluate the reuse potential of the different wastewater treatment products.

It should be noted that no scores are assigned for this criterion, but the potential for reuse of either the treated effluent, the solids and/or the nutrients, and/or the possibility of energy generation, should be factored in during the technology selection process.

TABLE 4.12

Analysis of the Reuse Potential of Products Resulting from a Treatment Process

PRODUCT	USE	TREATMENT LEVEL REQUIRED
Water	Restricted irrigation (crops that are not eaten raw by humans)	Secondary
	Unrestricted irrigation (crops such as fruit trees and olives, for example, which don't come into direct contact with the ground/irrigation water)	Secondary
	Unrestricted irrigation (root and leaf crops that may be eaten uncooked)	Tertiary
	Urban landscape irrigation (parks, road margins, sports facilities, and so on)	Tertiary
	Industrial uses	Varies: in some situations, industries will purchase secondary effluent and handle tertiary/advanced treatment themselves
	Environmental/surface flow	Secondary
	Seawater intrusion barrier through groundwater recharge	Secondary/tertiary
	Aquifer recharge	Tertiary/advanced
	Potable	Advanced
	Soil amendment	Sludge stabilization, conditioning, dewatering, drying and/or composting
Biosolids (solids and nutrients)	Solid fuel	Dewatering, drying
	Fuel briquettes	Charring
	Construction materials	Dewatering, drying
	Fertilizers (particularly phosphorus)	Chemical extraction or crystallization
	Fuel	Digestion + advanced conditioning
Biogas	Heat	Digestion + boilers
	Electricity	Digestion + treatment + combustion (through turbines, combustion engine/generator sets, direct drive engines or Stirling engines, for example)

Note: See "Levels of Wastewater Treatment" in Chapter 3 for the definitions of primary, secondary and tertiary treatment.

Climate Change Impact

Climate change considerations are usually not used as an independent criterion when selecting wastewater treatment technologies and have been included in the discussions regarding the other criteria presented earlier in this guide. The following text provides some insights with regard to the interface of wastewater treatment and climate change and will help the user in better incorporating these considerations at the prefeasibility and feasibility phases of the project cycle:

- Greenhouse gas (GHG) emissions associated with WWTPs can be both *direct* and *indirect*.
  - *Direct GHG emissions* are associated with gases that are released or produced during wastewater and sludge treatment processes, whether intentionally or as a by-product. Methane (CH_4) and nitrous oxide (N_2O) are the most important GHGs directly produced from excreta in sanitation systems. Over a 20-year time horizon, the global warming potential (GWP) of CH_4 is 81.2 times larger

than for carbon dioxide (CO_2), whereas for N_2O the GWP is 273. Over a horizon of 100 years, the GWP of CH_4 and N_2O, is 27.9 and 273 times larger than CO_2, respectively.[10] Direct CO_2 emissions from wastewater are not considered in the IPCC Guidelines because these are from a biogenic origin.

- *Indirect GHG emissions* are those caused by the use of energy and chemicals in the wastewater treatment process and in the generation, production and transportation of these chemicals to the WWTP. Electricity is particularly relevant for indirect GHG emissions, especially in countries where it is largely generated using coal or other fossil fuels. In such cases, the quantification of GHG impacts should consider either the country-specific mix employed in power generation or the site-specific energy mix if there will be any investment in onsite energy generation (diesel, solar photovoltaic systems, biogas capture, and so on). In some cases, water and wastewater treatment plants are the largest energy consumers in certain municipalities and can account for 30 to 40 percent of the total energy consumed. Chemicals used in the treatment process also contribute to indirect GHG emissions because of the energy embedded in them, but chemicals are typically not considered key components of WWTP operation.

- All direct and indirect GHG emissions at WWTPs are added together for each component of the treatment train and are converted into 'carbon dioxide equivalents' (CO_2e) based on the corresponding GWP factor.

- Wastewater treatment facilities can include anaerobic steps. CH_4 generated at such facilities can be recovered and combusted in a flare or energy device, and the amount of CH_4 handled this way at the plant should be subtracted from total emissions, through the use of a separate CH_4 recovery parameter. The amount of CH_4 transformed into CO_2 through flaring or energy generation should be included in the overall GHG emission calculation for the plant.

With these considerations in mind, the following can be said:

- When individual factors are viewed in isolation, high GHG emissions are seen to be associated with technologies that feature high electricity consumption, that target enhanced removal of nitrogen, and/or that include anaerobic stages in which the generated biogas is not captured.

- When individual factors are viewed in isolation, low GHG emissions are more likely to be observed for technologies with low electricity requirements that only target organic pollution (BOD_5) removal, even when this is combined with disinfection, and that do not include anaerobic treatment stages.

- There are trade-offs between these factors. For example, many anaerobic treatment technologies, such as deep ponds, have low energy requirements but can still emit significant methane emissions if biogas is not captured.[11]

Electricity consumption and GHG emissions thus show a similar trend: the higher a technology's energy requirements, the higher its GHG emissions associated with energy usage and the lower its score. This dimension of the potential GHG impacts of different WWTP technologies is partially captured in the earlier section on the technology criterion "Energy Use." Likewise, the GHG impact of treatment objectives is also indirectly captured in this way since enhanced nitrogen removal typically implies higher energy consumption. In addition, the negative impact of anaerobic stages on the overall GHG balance can be reduced or eliminated by collecting, capturing and flaring biogas or turning it into energy. This applies to anaerobic ponds, UASBs and ABRs.

Consequently, for the purpose of this guide, no stand-alone GHG or climate change criterion is included given the trade-offs between decisions that can affect both direct CH_4 and N_2O emissions as well as the indirect emissions from energy use, as discussed here. It is recommended that, as part of the prefeasibility and feasibility phases of the project, GHG analyses be undertaken along the above lines in order to compare treatment options and to assess whether capturing CH_4 could bring additional benefits.

In addition to GHG considerations, climate change adaptation is increasingly being recognized as important for defining the location and managing the performance of WWTPs. The potential effects of climate change on the design and operation of WWTPs should be factored in when selecting the location of the small town WWTP and when defining an appropriate treatment train for it, in order to improve its overall climate resilience (World Bank 2020).[12] For example, taking into account the hydrological risk associated with recurrent droughts when designing a WWTP could help minimize the impacts of reduced water consumption and wastewater flows on its performance and on the associated CAPEX and OPEX. Similarly, it is worth considering the current and future climate change-related flood risk when choosing a treatment site and the location of onsite equipment.

Notes

1. Graywater is defined as "water generated from washing food, clothes and dishware, as well as from bathing, but not from toilets. It may contain traces of excreta (e.g., from washing diapers) and, therefore, also pathogens" (Tilley and others 2014).
2. Based on the assumption of 0.25 L septage per capita per day and a concentration of 2,000 mg BOD_5/L (see, for example, sources cited in Footnote 3, comparing one person serviced through a sewer system producing a wastewater pollution of 50 g BOD_5/cap/day).
3. For overall principles and issues concerning fecal sludge management, see: (a) L. Strande, M. Ronteltap, and D. Brdjanovic, *Faecal Sludge Management-Systems Approach for Implementation and Operation* (London: IWA Publishing, 2014); for fecal sludge treatment plant design, see (b) K. Tayler, *Faecal Sludge and Septage Treatment: A Guide for Low and Middle Income Countries* (Rugby: Practical Action Publishing, 2018), https://practicalactionpublishing.com/book/693/faecal-sludge-and-septage-treatment; and for co-treatment of fecal sludge and wastewater, see (c) D. Narayana, *Co-treatment of Septage and Fecal Sludge in Sewage Treatment Facilities* (London: IWA Publishing, 2020).
4. The typical volume of trucks used for the collection of fecal sludge in small towns ranges from 3 to 10 m^3 (see K. Tayler, *Faecal Sludge and Septic Treatment: A Guide for Low and Middle Income Countries* (Rugby: Practical Action Publishing, 2018).
5. If the reader needs to compare with COD concentrations, COD effluent concentrations can be estimated (a) by multiplying effluent BOD_5 values by a factor of about 2.5 to 3.0 in case of effluent BOD_5 concentrations higher than 100 mg/L and (b) by multiplying BOD_5 concentrations by a factor of 3.0 to 5.0 for cases of low effluent BOD_5 (the lower the BOD_5 concentration is, the higher the factor).
6. See, for example, the 1989 and 2006 WHO guidelines: (a) WHO, "Health Guidelines for the Use of Wastewater in Agriculture and Aquaculture. Report of a WHO Scientific Group" (Geneva, Switzerland, November 18–23, 1987, 1989); and (b) WHO, "Excreta and Greywater Use in Agriculture," vol. 4 in *Guidelines for the Safe Use of Wastewater, Excreta and Greywater* (Geneva, Switzerland: WHO, 2006).
7. The not-in-my-backyard, or NIMBY, effect is the potential rejection by neighboring communities to having a wastewater treatment plant built and operating near their homes.
8. This guide refers to SpTPs as independent treatment plants that are specifically designed to treat septage delivered to these facilities in tankers.
9. Energy consumption in WWTPs is often reported as per the volume of treated wastewater or unit of population equivalent (PE) on an annual basis—that is, kWh/m^3/year or kWh/PE/year, respectively. Although international practice typically points to the use of an average influent PE60 where 1 PE60 = 60 g BOD_5/d or PE120 where 1 PE120 = 120 g COD/d, considered typical values of organic pollution discharged through wastewater by 1 capita in many developed countries, for small towns in LMICs, the value of PE40 is considered more accurate. These figures can vary with, for example, 35 g BOD_5/d (Morocco) and 50 g BOD_5/d (Brazil) values commonly used as well.
10. Preliminary figures from the Intergovernmental Panel on Climate Change (IPCC) AR6 WGI, "Chapter 7: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity – Supplementary Material," 7SM-24, https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter_07_Supplementary_Material.pdf. Figures still subject to final editing as of October 20, 2021.

11. It should also be noted that any emissions associated with latrine/septic tank use, with the fecal sludge/septage as well as wastewater collection systems, and with the disposal of sludge at landfills or at other disposal sites, are all outside of the scope of those emissions that can be solely attributed to the treatment stages, and are thus considered beyond the scope of this guide.

12. See, for example, A. Zouboulis and A. Tolko, "Effect of Climate Change in Wastewater Treatment Plants: Reviewing the Problems and Solutions," in S. Shrestha, A. Anal, P. Salam, M. van der Valk (eds) *Managing Water Resources under Climate Uncertainty*, pp 197–220 (Cham: Springer International Publishing, 2015).

Applying This Guide in Practice: A Step-by-Step Approach

5

The selection of appropriate wastewater treatment technologies for small towns presents a challenge to national, regional and local policy makers and decision makers because (a) recent technological developments provide a large menu of options for the treatment of wastewater and (b) small towns often lack financial, technical and human resources to implement the treatment solutions commonly used for larger populations.

The selection process will depend on where the solution is being implemented and which factors are deemed most important by the decision makers and other stakeholders. This section, drawing on concepts presented earlier, applies a suggested five-step approach for decision makers to identify appropriate wastewater treatment plants (WWTPs) for small towns. The approach will be detailed for each step, describing the aim, the suggested process to be followed, the expected result and any additional considerations.

The guide methodology and overall selection process is demonstrated in Chapter 6 through the use of case studies.

Methodology: Overview of Suggested Five-Step Approach

The criteria detailed in the present subsection form the crux of the guide's methodology, which aims to provide small towns with decision-making support in the identification of appropriate wastewater treatment solutions. To apply this guide to a real-life situation, decision makers should rely on a five-step approach (see Figure 5.1).

1. *Familiarize themselves with the guide methodology,* as described in prior sections.
2. *Convene key stakeholders to discuss the project criteria* and agree, through workshops and/or focus groups discussions, on the characteristics of the town(s) as per the different criteria presented herein. This guide suggests six core project criteria that outline important characteristics of the small town to consider for the choice of a wastewater treatment system as they relate to population, growth, local activities, and existing services and practices.
3. *Convene key stakeholders to discuss the project criteria* by holding discussions on the acceptable values for the technology criteria based on the local context. The technology criteria are based on each technology's specifications, and their value

FIGURE 5.1

Overview of the Key Steps in the Application of This Guide

is therefore set in each technology sheet, independent of the local context.

4. *Identify the nonnegotiable or exclusion criteria* to narrow down the list of potential technologies and treatment trains and *agree upon the priorities* (for example, minimal energy use, minimizing space requirements, potential for wastewater reuse for agriculture, and so on). It is important to identify which technology criteria are nonnegotiable because of local constraints or other priorities/factors. It is also important to determine which provide more flexibility so they can be marked accordingly in the application of the guide's methodology and so help eliminate technologies that do not meet the identified requirements.

5. After *assigning weighting to technology criteria and calculating total scores for the remaining technologies*, decision makers should arrive at a reduced list of applicable technologies and/or treatment trains. Based on these options, *a preselection and/or decision can be made* regarding the appropriate technology train for the small town in question.

Step 1: Familiarize Yourself with the Guide's Methodology

The aim of this step is to become familiar with the foundational theory and application of the guide before following the subsequent steps of the suggested five-step approach. This entails understanding the context of the small town, and of wastewater treatment technologies for small towns, and then drawing up preliminary considerations of the project and technology criteria. At the end of Step 1, the user of the guide should have a strong understanding of the basic concepts of small-town wastewater treatment technologies and be prepared to apply the guide in the subsequent planning/assessment process.

Step 2: Convene Key Stakeholders to Discuss the Project Criteria

The aim of Step 2 is to find agreement on the project criteria through workshops and focus group discussions. The discussion on project criteria allows for relevant stakeholders to mutually agree on the conditions that will influence technology selection for a given small-town WWTP. Although stakeholders are, at this stage, not yet likely to be able to define all project conditions very accurately, the order of magnitude of certain criteria or their tentative importance need to be agreed upon before the technology criteria can be applied. This relates, for instance, to issues such as the population to be connected through sewers to the WWTP, how much land is available for the WWTP, how reliable power supply is at the suggested WWTP site, whether the WWTP is expected to deliver a high-quality effluent or primarily only remove the bulk of pollution, and so on.

The guide suggests six core project criteria that outline important characteristics of the small town to consider for the choice of a wastewater treatment system. The following brief discussion and Figure 5.2 summarize the suggested project criteria (for more details, see Chapter 4 "Project

FIGURE 5.2
Project Criteria

Feasibility of sewerage	For this criterion, an analysis of whether there is sufficient housing density and sufficient water supply—and thus wastewater discharge—available will be developed, which would justify the implementation of a sewer system and WWTP.
Total connections to the WWTP	A rough estimate of the total expected capita (equivalents) that shall be connected to the WWTP should be developed. This involves estimating, among other aspects, not only the actual population, connection percentages, and converting industrial discharges into capita equivalents but also forecasting future developments. The outcome of this estimation exercise will determine whether the total connections and thus expected WWTP capacity are indeed within the range for which this small town guide was developed. In addition, this criterion will help assess, for instance, absolute land and power requirements for the WWTP.
Fecal sludge	This criterion will help define if the fecal sludge collected in the small town can also be transported to and treated at the WWTP or if a separate system for fecal sludge management and treatment needs to be established. Whether the latter is required, there is no need for consideration of fecal loads in the WWTP design.
Regulations for treated discharge and reuse	The required level of treatment plays a key role in technology selection because not all technologies can deliver any given quality requirement. It is thus important to agree on the required treatment standards.
Available land for the WWTP	As a rule of thumb, it can be stated that the smaller the available land area for a WWTP is, the more intensive the technology needs to be, and vice versa. Thus, large available land areas allow for the implementation of technologies that are cheaper to operate and that require less-qualified personnel.
Power supply to the WWTP	Stakeholders also need to develop an understanding of the potential for power supply to the WWTP site. Some technologies depend fully on permanent and high levels of power supply, whereas others may not require any power at all. High power needs usually require a robust grid connection and reliable power supply, whereas medium to low power requirements might also be generated onsite from renewable resources, such as biogas or photovoltaic panels.

Note: WWTP = wastewater treatment plant.

Criteria"), explaining why each plays an important role in the selection of appropriate wastewater treatment technologies.

Schematic Work Plan for Step 2

As part of Step 2, key stakeholders need to determine the applicability of the guide methodology as illustrated in Figure 5.3 and in agreement with the characteristics of the small town presented in chapter 4 "Project Criteria."

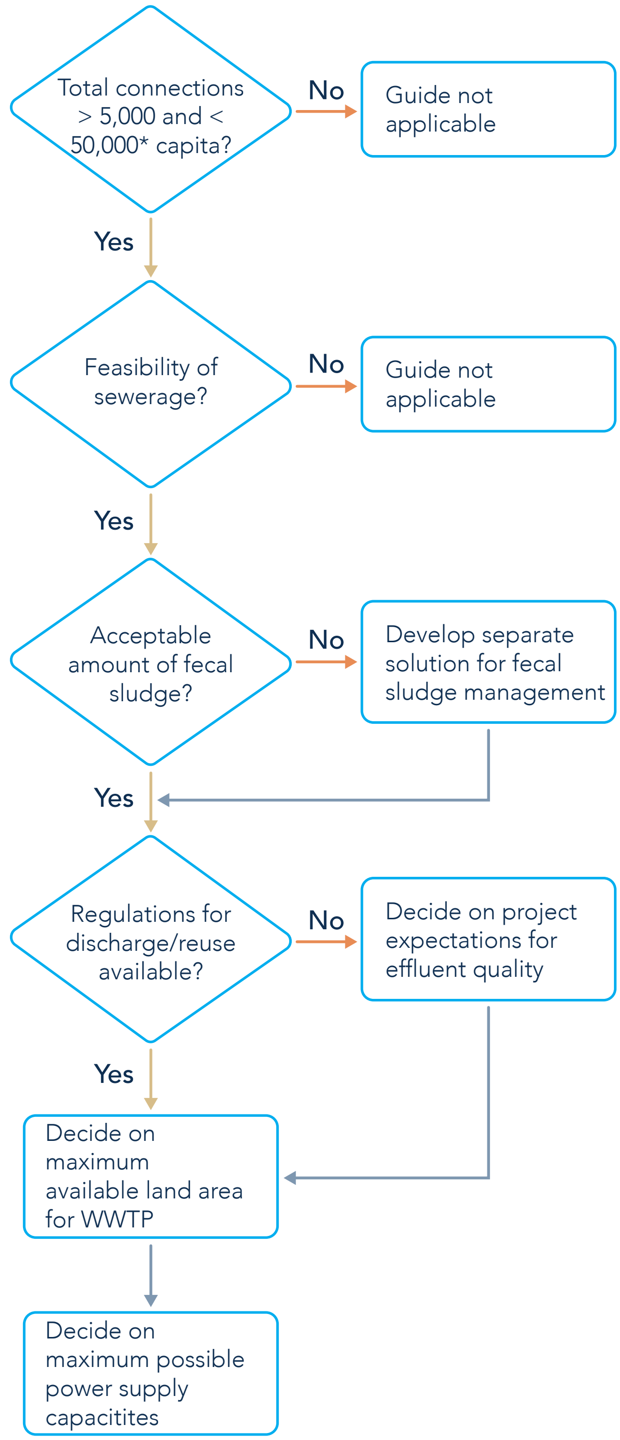
At the end of Step 2, the stakeholders should have recorded their tentative agreement on the characteristics of the small town, including information on population, growth, local activities and existing services and practices, which will inform Step 3.

Step 3: Convene Key Stakeholders to Discuss the Project Criteria

The aim of this step is to find agreement on the acceptable values for the technology criteria through workshops and focus group discussions. Step 3 requires discussion about the technology criteria for which the guide suggests a total of eleven criteria (see Chapter 4 "Technology Criteria" for details), as shown in Figure 5.4.

Stakeholders may wish to add additional criteria and/or eliminate some of the suggested criteria based on the local context. Similarly, if local cost data are available, stakeholders should modify the operation and maintenance (O&M) cost/investment cost criteria with the use of specific values (according to acceptable cost levels for the town[s]) rather than use the relative low/medium/high assessment given in Chapter 4 "Technology Criteria." This process needs to be undertaken only for technologies that are being considered

FIGURE 5.3
Schematic Work Plan for Step 2



* Can be as high as 100,000 people (mostly in Asian countries).
Note: WWTP = wastewater treatment plant.

FIGURE 5.4

Technology Criteria

Technical/environmental criteria	Financial criteria	Other important considerations
• Treatment efficiency • Ease of upgrading to enhanced or biological nutrient removal (BNR) • Land availability • Labor qualification • Availability of replacement parts and O&M inputs • Sludge production • Energy use	• O&M costs (OPEX) • Investment/capital costs (CAPEX)	• Reuse potential • Climate change impact

Note: CAPEX = capital expenditures; O&M = operation and maintenance; OPEX = operating expenditures.

for a given context (that is, some technologies may already have been ruled out).

At the end of Step 3, the stakeholders should have agreement on potential changes to and/or specifications for the values that they have adopted for the technology criteria.

Step 4: Identify and Apply Nonnegotiable or Exclusion Criteria

The objective of Step 4 is for the stakeholders to collectively determine which technology criteria are nonnegotiable due to local constraints or priorities and which provide more flexibility. These criteria should be assessed by following the guidance provided herein and can thus help eliminate technologies that do not meet the identified requirements. By making reference to the outcome of the discussion on project criteria (Step 2), the users will be able to approach technology selection with an improved understanding of which criteria will have a more significant impact on a specific WWTP project and will be able to decide which of these should be understood as nonnegotiable or exclusion criteria. Steps 3 and 4 will thus first define and apply the exclusion criteria, leading to a narrowed down list of technologies, which will be further analyzed in Step 5, as described in the next section.

For instance, technologies with a larger footprint requirement should be excluded if the land available for the WWTP is limited. Similarly, technologies that cannot achieve a specific required treatment efficiency should be eliminated, and those that present capital expenditure (CAPEX) or operating expenditure (OPEX) figures beyond the operating utility's capacity should similarly not be included in the subsequent steps of the assessment. In another example, the ability to meet the required discharge quality or space requirements may be nonnegotiable depending on the sensitivity of the receiving body of water or the space available.

By the end of this step, and after the application of the nonnegotiable and/or the exclusion criteria, stakeholders should have reduced the list of potential technologies and treatment trains for consideration in the next step. In addition, stakeholders should agree upon local context priorities, such as minimal energy use, minimizing space requirements, potential for wastewater reuse for agriculture, and so on.

Step 5: Assign Weighting to Technology Criteria and Calculate Total Score for Remaining Technologies

The aim of Step 5 is to assign weights to the technology criteria and to calculate the total scores for the remaining technologies. This can be seen as a subjective exercise as it will be dependent on the perspectives of the decision makers involved in the selection of the appropriate technologies for the given small town. Nevertheless, because the objective of this guide is to support its users in bringing together all the information considered relevant for decision making, this weighting exercise is seen as a practical way to help narrow down the number of technologies appropriate for a specific context.

For each technology that was considered appropriate for small-town WWTPs, Chapter 4 "Technology Criteria" suggests a scoring table for all technology criteria, except for the reuse potential and climate change impact aspects, for which qualitative guidance is instead provided.

The user is free to apply the suggested scores or, alternatively, develop a set of customized scores for the technology criteria in question, which should thereafter be weighted to arrive at the calculation of a total score. The highest score should then be considered as the best option based on the decision makers' assumptions and conditions.

Step 5 should culminate in the establishment of a reduced list of applicable technologies and/or treatment trains from which a preselection and/or decision can be made on the appropriate technology train for the small town in question.

In addition, the case studies presented in Chapter 6 provide working examples on how this approach can be applied.

Schematic Work Plan for Steps 3 to 5

The step-by-step methodology described earlier for Steps 3 to 5 is summarized in Figure 5.5.

How to Weight Criteria and Calculate Total Scores

This section provides an overview of how to perform the criteria weighting exercise. A summary table of nine technology criteria and their respective scores is first presented, with the exception of two of the criteria—reuse potential and climate change impact—for which qualitative guidance has been provided earlier in the guide. Those scores are thereafter weighted, and a total score is calculated.

Table 5.1 presents a matrix of the nine technology criteria and the preselected technology options. It presents the suggested standard scoring defaults in which a technology with a higher score would be considered more advantageous regarding a certain criterion (3 being the highest score and 1 the lowest). For example, in terms of land availability, an ABR

FIGURE 5.5
Schematic Work Plan for Steps 3 to 5

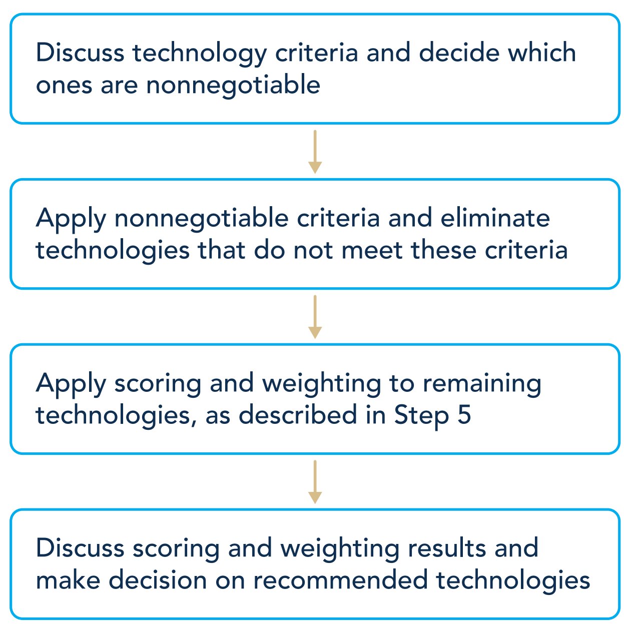


TABLE 5.1

Summary of Suggested Scores for Each Technology (Standard Defaults)

TECHNOLOGY		TECHNOLOGY CRITERION								
		4.2.1	4.2.2	4.2.3	4.2.4	4.2.5	4.2.6	4.2.7	4.2.81	4.2.9
#		TREATMENT EFFICIENCY	EASE OF UPGRADING TO BNR	LAND AVAILABILITY	LABOR QUALIFICATIONS	AVAILABLE PARTS + O&M INPUTS	SLUDGE PRODUCTION	ENERGY USE	OPEX	CAPEX
Primary treatment (only)										
1	ST	1	1	3	3	3	3	3	3	3
2	BD	1	1	3	3	3	3	3	3	3
3	IMH	1	1	3	3	3	3	3	3	2
Primary + secondary treatment										
4	ABR	2	1	3	3	3	3	3	3	3
5	ANF	2	1	3	3	3	2	3	3	2
6	WSP	2	1	1	3	3	3	3	3	2
7	AL	2	1	1	1	1	3	2	2	2
8	CW(1-st)	3	2	1	3	3	1	2	3	1
9	CW(hybrid)	3	3	1	3	3	2	3	3	1
10	UASB	2	1	2	1	3	2	3	2	2
11	EA	3	3	3	1	1	1	1	1	1
12	SBR (EA)	3	3	3	1	1	1	1	1	1
13	TF	3	2	3	2	2	1	2	2	1
14	RBC	3	2	3	2	2	1	2	2	1
15	UASB-WSP	3	1	1	1	3	2	3	2	1
16	UASB-Tf	3	2	3	1	2	1	2	2	1
Tertiary treatment (additional)										
17	UV	N/A	N/A	3	1	1	N/A	3	3	3
18	Cl	N/A	N/A	3	1	2	N/A	3	3	3
19	PP	N/A	N/A	2	3	3	3	3	3	3
20	RF	N/A	N/A	2	3	3	3	3	3	3
21	RDF	N/A	N/A	3	1	1	1	3	3	3

Note: ABR = anaerobic baffled reactor; AL = aerated lagoon; ANF = anaerobic filter; BD = biogas digester; BNR = biological nutrient removal; CAPEX = capital expenditures; Cl = chlorination; CW(1-st) = one-stage constructed wetland; CW(hybrid) = hybrid constructed wetland; EA = extended aeration; IMH = Imhoff tank; N/A = not applicable; O&M = operation and maintenance; OPEX = operating expenditures; PP = polishing pond; RBC = rotating biological contactor; RDF = rotary disc filter; RF = rock filter; SBR(EA) = sequencing batch reactor (extended aeration variant); ST = septic tank; TF = trickling filter; UASB = upflow anaerobic sludge blanket reactor; UASB-TF = UASB followed by a TF; UASB-WSP = UASB followed by a WSP; UV = ultraviolet; WSP = waste stabilization pond.

that requires an average area of 0.30 square meters per capita is assigned a score of 3 and would be considered more advantageous than a WSP that requires an average area of 4.75 square meters per capita and is thus assigned a score of 1. Detailed explanations of the scoring rationale can be found in Chapter 4 "Technology Criteria".

To produce a total score for each technology using the individual scores presented in Table 5.1, thus permitting an overall comparison of technologies, a weight should be assigned to each criterion, taking into account that not all of the criteria may be of equal importance to a specific situation. The exercise described in this section will generate scores for the seven technical criteria and the two financial criteria listed in the table. It is further proposed to group the technical and the financial criteria and to give equal weight to these two groups—that is, the total of the scoring resulting from criteria 1 to 7 receives an overall 50 percent weight, and the total of the scoring from criteria 8 and 9 also receives a 50 percent weight.

The grouped scores are worked out as an average of the total scores of each grouping. Table 5.2 presents an example of the outcome of a grouping and weighting exercise, with 3 continuing to be the maximum achievable score per criterion.

The users of the guide are free to modify the standard approach described above, as deemed appropriate for the small town in question. In doing so, the proposed standard 1-2-3 scores for each criterion could be revised, as could the weighting. Furthermore, additional criteria together with their associated scores, could be added to the list of the eleven proposed criteria, and/or certain criteria could be removed from consideration, depending on the project circumstances. Nevertheless, it is strongly advised that if substantial revisions are made to the presented approach, then experienced specialists should be included in the stakeholder discussions to help make technically sound decisions. In situations in which this may not be possible, or in which the users of the guide are less experienced with technology selection, it is advised to use the standard recommendations provided here. In any case, whether the proposed standard approach or a modified approach is used, definitions and decisions should always properly reflect local conditions and the preferences of the relevant stakeholders. In addition, the users also need to incorporate qualitative information provided by employing the reuse potential and climate change impact criteria when interpreting the results.

It should also be kept in mind that the resulting total weighted score is not a fixed result but rather the outcome of assumptions and subjective assessments and, as such, should be considered with the flexibility inherent in the prefeasibility and feasibility phases of a project cycle. Furthermore, the user should continue to take into account the potential combinations of technology trains presented in Table 3.5 ("Typical Wastewater Treatment Trains for Preselected Treatment Technologies for Small-Town WWTPs") and Table 3.6 ("Typical Sludge Treatment Trains for Preselected Treatment Technologies for Small-Town WWTPs") during the prefeasibility and feasibility phases of the project cycle, which will be further illustrated in the case studies presented in Chapter 6.

The typical outcome of applying the guide's methodology should not point to a single optimum technology but rather to a group of technologies that represent the best, or near-best, score, each of which thus potentially representing a sound and appropriate wastewater treatment solution for a specific small town and each of which then deserve further detailed analysis.

TABLE 5.2

Summary of Weighted Scoring for Each Technology, Based on Suggested Standard Defaults

TECHNOLOGY		TECHNICAL/ENVIRONMENTAL CRITERIA		FINANCIAL CRITERIA		WEIGHTED SCORE		
#		AVERAGE SCORE CRITERIA #1–7	WEIGHT OF CRITERIA #1–7	AVERAGE SCORE CRITERIA #1–7	WEIGHT OF CRITERIA #8–9	CRITERIA #1–7	CRITERIA #1–7	TOTAL
Primary treatment (only)								
1	ST	2.43	50%	3.00	50%	1.21	1.50	**2.71**
2	BD	2.43	50%	3.00	50%	1.21	1.50	**2.71**
3	IMH	2.43	50%	2.50	50%	1.21	1.25	**2.46**
Primary + secondary treatment								
4	ABR	2.57	50%	3.00	50%	1.29	1.50	2.79
5	ANF	2.43	50%	2.50	50%	1.21	1.25	2.46
6	WSP	2.29	50%	2.50	50%	1.14	1.25	2.39
7	AL	1.57	50%	2.00	50%	0.79	1.00	1.79
8	CW(1-st)	2.14	50%	2.00	50%	1.07	1.00	2.07
9	CW(hybrid)	2.57	50%	2.00	50%	1.29	1.00	2.29
10	UASB	2.00	50%	2.00	50%	1.00	1.00	2.00
11	EA	1.86	50%	1.00	50%	0.93	0.50	1.43
12	SBR (EA)	1.86	50%	1.00	50%	0.93	0.50	1.43
13	TF	2.14	50%	1.50	50%	1.07	0.75	1.82
14	RBC	2.14	50%	1.50	50%	1.07	0.75	1.82
15	UASB-WSP	2.00	50%	1.50	50%	1.00	0.75	1.75
16	UASB-TF	2.00	50%	1.50	50%	1.00	0.75	1.75

Note: ABR = anaerobic baffled reactor; AL = aerated lagoon; ANF = anaerobic filter; BD = biogas digester; CW(1-st) = one-stage constructed wetland; CW(hybrid) = hybrid constructed wetland; EA = extended aeration; IMH = Imhoff tank; RBC = rotating biological contactor; SBR(EA) = sequencing batch reactor (extended aeration variant); ST = septic tank; TF = trickling filter; UASB = upflow anaerobic sludge blanket reactor; UASB-TF = UASB followed by a TF; UASB-WSP = UASB followed by a WSP; WSP = waste stabilization pond.

Case Studies

6

The three case studies presented below—from Morocco, Vietnam and El Salvador, respectively—provide specific examples of applying the different criteria and working through the guide's methodology, which can be helpful in conceptualizing the application of the guide's approach to a specific context.

Case 1: Small Town in Morocco

The analysis of this case study follows the general methodology described in Chapter 5.

Step 1: Familiarize with GUIDE METHODOLOGY

Decision makers from ONEE, Morocco's National Electricity and Water Office, convened and familiarized themselves with the approach.

Step 2: PROJECT CRITERIA

The project criteria described in Chapter 4 of the guide were discussed by the decision makers, and Table 6.1 was produced to summarize the outcome.

TABLE 6.1
Project Criteria for the Morocco Case

PROJECT CRITERION	COMMENTS
1. Feasibility of sewer	
Responsibility for water supply and sanitation service delivery	Water, sanitation, and electricity are all handled by the same utility: ONEE.
Water availability	Most households in small towns are connected to the public water network (consumption is approximately 50 L/cap/day), though water availability may vary (water availability in Morocco has dropped over the past decades and has reached physical scarcity levels).
Stormwater management	Sewage and stormwater are managed separately (i.e., there is no combined system). It was also established that the drainage of stormwater is properly maintained and working well, enabling the construction of cost-efficient separate sewers.
Solid waste management	It was agreed that solid waste should have a minimal/negligible impact. It is collected and disposed of adequately.
Conclusions	**Sewer system appears feasible**

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TABLE 6.1

Project Criteria for the Morocco Case (*Continued)*

PROJECT CRITERION	COMMENTS
2. Total connections to WWTP	
Project horizon	20 years
Residential population	20,000 people
Sewer connection rate	A 90% connection rate was assumed.
Industrial waste streams	Industrial waste streams are present, particularly from olive oil mills/presses (*margines*), with a high concentration of phenols. All stakeholders agreed that the wastewater pollution from these sources may be high, though it is generated only seasonally. Without specific data on this waste stream, it was agreed to assume a maximum industrial pollution equal to about 5,000 PE.
Fecal sludge and/or septage	Dumping of fecal sludge at WWTPs is not common and was not considered a factor.
Urban/industrial growth	1.5% annual growth, mostly attributable to vegetative growth. No industrial growth.
Conclusions	Total future population = ca. 27,000 PE Connected total future population = ca. 24.000 PE Industrial loads = 5,000 PE **Total estimated capacity of WWTP = 29,000 PE**
3. Fecal sludge	
Conclusions (see item 2)	**Possible overloading of the WWTP by fecal sludge is not considered a factor.**
4. Regulations for treated discharge and reuse	
Discharge regulations	Regulation for WWTP discharges to receiving waters exist in Morocco and focus exclusively on removal of organic pollution, with $BOD_5 \leq 120$ mg/L. There are no nutrient standards for nitrogen and phosphorus.
Reuse regulations	No major regulatory (environmental) constraints, although the legal and regulatory framework for wastewater reuse is incomplete, leading to common informal reuse of raw or treated wastewater, which poses important health risks. New regulations in this regard are currently under development. In general, irrigation standards in Morocco require a minimum hygienic quality, with fecal coliforms ≤ 1,000 MPN/100mL and an absence of nematode ova.
Conclusions	**Standards for discharge quality exist and are defined primarily by requirements for removal of organic pollution—that is, $BOD_5 \leq 120$ mg/L. Reuse for irrigation is not a project criterion, but if effluent is hygienically safe, this could constitute an added benefit.**
5. Available land for the WWTP	
Land assigned for WWTP	Space is available and will not constrain any new construction for a wastewater and sludge treatment plant. The intention is to locate the WWTP relatively distant from the residential areas to avoid any odor or other issues.
Elevation	No major pumping head is required. The additional distance sought to minimize issues with odors may increase the pumping costs, but this is accepted as a nonavoidable cost.
Flood protection	There is no flooding risk at the potential WWTP sites.
Geotechnical characteristics	The soil is generally rather stony. No issues are expected with heavy structures.
Reserves for later expansion	There is sufficient land for future expansion.
Conclusions	**No issues are foreseen at this point with finding suitable land for the WWTP.**

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TABLE 6.1

Project Criteria for the Morocco Case (*Continued)*

PROJECT CRITERION	COMMENTS
6. Power supply to the WWTP	
Reliability of electricity	Electricity is available and reliable.
Maximum possible capacity	No clear conclusion could be drawn concerning the maximum power capacity, and moderate to low power requirements should therefore be targeted. This will increase safety and reduce OPEX.
Onsite generation of power	Solar power generation could be an option because there is plenty of sunshine and strong solar radiation in the area. However, project stakeholders were uncertain as to whether such a source of electricity would be sufficient for the WWTP and/or whether it should serve to provide emergency power backup.
Conclusions	**Electricity from the grid is safely and reliably available. Moderate to low power consumption is preferred. Solar panels may also be considered.**

Note: BOD_5 = five-day biological oxygen demand; ONEE = Morocco's National Electricity and Water Office; OPEX = operating expenditures; PE = population equivalent; WWTP = wastewater treatment plant.

In summary, and using the decision tree presented in figure 5.3 as a guide, Step 2 concludes that (a) this guide is applicable; (b) a sewer system is indeed feasible; (c) fecal sludge disposal/cotreatment will not be a relevant factor or constraint; (d) there are clear definitions of the required treated wastewater quality; and (e) both land and power are sufficiently available.

Step 3: TECHNOLOGY CRITERIA

The technology criteria described in chapter 4 of the guide were discussed by the decision makers, and table 6.2 was produced to summarize the outcome.

TABLE 6.2

Technology Criteria and Exclusion Criteria for the Morocco Case

TECHNOLOGY CRITERION	COMMENTS	EXCLUSION OF TECHNOLOGIES?
Treatment efficiency	As described in table 6.1, effluent treatment targets are defined by: ■ BOD_5 ≤120 mg/L; and ■ The desire (but not legally binding requirement) for a hygienically safe effluent quality to minimize risks associated with (currently unofficial) reuse in irrigation.	Comparing the treatment targets with the information provided in chapter 4 "Treatment Efficiency," it becomes clear that primary treatment options only (**ST, BD, and IMH**) cannot comply with the required BOD_5 limit and thus **need to be excluded**. No technology should be excluded because of the hygienic requirements because all those technologies could be equipped with a separate tertiary disinfection stage. However, it is noted that WSPs could help avoid such an additional stage because they effectively remove pathogens as part of their treatment process, an advantage that should be considered at a later stage (weighting of technologies).

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TABLE 6.2

Technology Criteria and Exclusion Criteria for the Morocco Case (*Continued*)

TECHNOLOGY CRITERION	COMMENTS	EXCLUSION OF TECHNOLOGIES?
Ease of upgrading to enhanced nutrient removal	No such future requirements are expected by the decision makers.	**This criterion is consequently considered irrelevant.**
Land availability	Land availability is not considered an issue, as concluded in table 6.1	Notwithstanding, and although a **smaller footprint is assumed to constitute an advantage, no technology is to be excluded because of this criterion.**
Labor qualification	Technical capacity of the WWTP operator (ONEE) is of a high level, though low-tech treatment processes are typically used. High-tech solutions are often used in cooperation with the private sector, and ONEE is in the process of building its capacity to implement more high-tech solutions for small towns. Although the technical and financial capacities are both at a high level, staff numbers are limited. In addition, staff are often asked to operate or supervise numerous treatment plants often far apart from one another. Minimizing O&M labor requirements may thus be desirable.	Finding or hiring sufficient skilled laborers is considered feasible for any technology, and **no technology exclusion is thus considered necessary for this criterion**. However, technologies with lower skill requirements should be scored higher.
Availability of replacement parts and O&M inputs	ONEE's administrative capacity is sufficient at both the central and regional levels to support operators and provide a regular supply of consumables and spare parts. As this small town is relatively close to a larger city, the need for replacement parts or O&M inputs is not considered a risk factor.	**No technology exclusion is required.**
Sludge production	Sludge production as such is not considered to constitute a significant issue, as sludge can be easily stored onsite at the WWTP or reused by local farmers. It is, however, recognized that a requirement for daily sludge removal may be problematic and/or will require higher personnel presence and thus OPEX.	**No technology exclusion is required, though weighting should give preference to technologies with low desludging frequencies.**
Energy use	Energy supply is considered to be reliable.	**No technology exclusion is required, though weighting should give preference to technologies with low energy consumption.**
OPEX	Decision makers agreed to select technologies with low operating costs, even though tariff and cost recovery levels allow for more expensive technologies to be implemented.	All technologies with an **OPEX score of 1 (see table 5.1) are excluded, namely EA and SBR(EA).**

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TABLE 6.2

Technology Criteria and Exclusion Criteria for the Morocco Case *(Continued)*

TECHNOLOGY CRITERION	COMMENTS	EXCLUSION OF TECHNOLOGIES?
CAPEX	The National Urban Sanitation Master Plan (which includes small towns) defines financing for the sector as shared between ONEE (50%) and municipalities (50%—either provided themselves or with support from the Ministry of the Interior). Financing from ONEE is generally available, but projects cannot move forward if the remaining portion has not been secured by municipalities, which may end up dictating the level of CAPEX that can be made available for these small towns.	All technologies with a **CAPEX score of 1 (see table 5.1) are excluded, namely CW(1-st), CW(hybrid), EA, SBR(EA), TF, RBC, and UASB-WSP and UASB-TF.**
Reuse potential	Reuse is not currently planned, though the informal reuse practice has already been phased into the assessment of technology criterion 1: treatment efficiency. No further considerations are deemed necessary.	**No technology exclusion is required.**
Climate change impact	The information in chapter 4 "Climate Change Impact" states that higher GHG emissions are typically associated with high energy consumption and with anaerobic stages. The former dimension is included in technology criterion 7: energy use and does thus not require further consideration. As for the latter, and even though all decision makers could not fully agree whether GHG emissions should indeed be considered as a relevant criterion for their WWTP, it was decided that technologies incorporating anaerobic stages would be excluded from further consideration in this particular case.	**Treatment technologies incorporating anaerobic stages are here excluded, namely anaerobic ponds and UASBs. In addition, ABR, ANF, and all primary treatment stages are excluded, as they involve anaerobic processes.** Nevertheless, if anaerobic technologies would constitute the only remaining options after this exercise, this criterion should not be applied.

Note: ABR = anaerobic baffled reactor; ANF = anaerobic filter; BD = biogas digester; BOD_5 = five-day biological oxygen demand; CAPEX = capital expenditures; CW(1-st) = one-stage constructed wetland; CW(hybrid) = hybrid constructed wetland; EA = extended aeration; GHG = greenhouse gas; IMH = Imhoff tank; O&M = operation and maintenance; ONEE = Morocco's National Electricity and Water Office; OPEX = operating expenditures; RBC = rotating biological contactor; SBR(EA) = sequencing batch reactor (extended aeration variant); ST = septic tank; TF = trickling filter; UASB = upflow anaerobic sludge blanket reactor; UASB-TF = UASB followed by a TF; UASB-WSP = UASB followed by a WSP; WSP = waste stabilization pond; WWTP = wastewater treatment plant.

Step 4: NONNEGOTIABLE or EXCLUSION CRITERIA

As described in chapter 5 "Step 4: Identify and Apply Nonnegotiable or Exclusion Criteria," the decision makers determined which technology criteria were nonnegotiable because of local constraints and priorities and which provide more flexibility. These criteria were marked accordingly in the application of this step and helped to eliminate technologies that did not meet the prior identified requirements.

TABLE 6.3

Summary of Excluded Technologies for the Morocco Case

TECHNOLOGY		TECHNOLOGY CRITERION LEADING TO EXCLUSION										
		4.3.1	4.3.2	4.3.3	4.3.4	4.3.5	4.3.6	4.3.7	4.3.8	4.3.9	4.3.10	4.3.11
#		TREATMENT EFFICIENCY	EASE OF UPGRADING TO BNR	LAND AVAILABILITY	LABOR QUALIFICATION	AVAILABLE PARTS + O&M INPUTS	SLUDGE PRODUCTION	ENERGY USE	OPEX	CAPEX	REUSE POTENTIAL	CLIMATE CHANGE IMPACT
Primary treatment (only)												
1	ST	excluded	OK	OK	OK	OK	OK	OK	OK	OK	excluded	excluded
2	BD	excluded	OK	OK	OK	OK	OK	OK	OK	OK	excluded	excluded
3	IMH	excluded	OK	OK	OK	OK	OK	OK	OK	OK	excluded	excluded
Primary + secondary treatment												
4	ABR	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	excluded
5	ANF	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	excluded
6	WSP	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK[a]
7	AL	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
8	CW(1-st)	OK	OK	OK	OK	OK	OK	OK	OK	excluded	OK	OK
9	CW(hybrid)	OK	OK	OK	OK	OK	OK	OK	OK	excluded	OK	OK
10	UASB	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	excluded
11	EA	OK	OK	OK	OK	OK	OK	OK	excluded	excluded	OK	OK
12	SBR (EA)	OK	OK	OK	OK	OK	OK	OK	excluded	excluded	OK	OK
13	TF	OK	OK	OK	OK	OK	OK	OK	OK	excluded	OK	OK
14	RBC	OK	OK	OK	OK	OK	OK	OK	OK	excluded	OK	OK
15	UASB-WSP	OK	OK	OK	OK	OK	OK	OK	OK	excluded	OK	excluded
16	UASB-TF	OK	OK	OK	OK	OK	OK	OK	OK	excluded	OK	excluded
Tertiary treatment (additional)												
17	UV	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
18	Cl	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
19	PP	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
20	RF	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
21	RDF	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK

Note: ABR = anaerobic baffled reactor; AL = aerated lagoon; ANF = anaerobic filter; BD = biogas digester; BNR = biological nutrient removal; CAPEX = capital expenditures; Cl = chlorination; CW(1-st) = one-stage constructed wetland; CW(hybrid) = hybrid constructed wetland; EA = extended aeration; IMH = Imhoff tank; O&M = operation and maintenance; OPEX = operating expenditures; PP = polishing pond; RBC = rotating biological contactor; RDF = rotary disc filter; RF = rock filter; SBR(EA) = sequencing batch reactor (extended aeration variant); ST = septic tank; TF = trickling filter; UASB = upflow anaerobic sludge blanket reactor; UASB-TF = UASB followed by a TF; UASB-WSP = UASB followed by a WSP; UV = ultraviolet; WSP = waste stabilization pond.

[a] WSP are acceptable; only anaerobic ponds should be excluded.

The only remaining technologies meeting the decision makers' criteria and preferences are waste stabilization ponds (WSPs), preferably without an anaerobic stage or pond, and aerated lagoons (ALs). In addition, because WSPs and ALs can be designed to meet the effluent quality requirements of this project, none of the tertiary treatment steps (UV [ultraviolet], Cl [chlorination], PP [polishing pond], RF [rock filter], and RDF [rotary disc filter]) would be necessary.

Step 5: Assign WEIGHTING to technology criteria, calculate TOTAL SCORE for remaining technologies

The scores proposed in table 5.1 are used here, and the suggested weighting approach of assigning equal weight to technical/environmental criteria and financial criteria. The criteria for ease of upgrading to BNR is excluded from consideration because it was considered irrelevant by the decision makers.

Tables 6.4 and 6.5 present the outcome of that scoring and weighting exercise, with 3 continuing to be the maximum achievable score.

TABLE 6.4
Summary of Scoring for Remaining Technologies after Step 4 for the Morocco Case

TECHNOLOGY	TECHNOLOGY CRITERION										
	4.3.1	4.3.2	4.3.3	4.3.4	4.3.5	4.3.6	4.3.7	4.3.8	4.3.9	4.3.10	4.3.11
#	TREATMENT EFFICIENCY	EASE OF UPGRADING TO BNR[a]	LAND AVAILABILITY	LABOR QUALIFICATION	AVAILABLE PARTS + O&M INPUTS	SLUDGE PRODUCTION	ENERGY USE	OPEX	CAPEX	REUSE POTENTIAL[b]	CLIMATE CHANGE IMPACT[b]
Primary + secondary treatment											
6 WSP	2		1	3	3	3	3	3	2		
7 AL	2		1	1	1	3	2	2	2		

Note: AL = aerated lagoon; BNR = biological nutrient removal; CAPEX = capital expenditures; O&M = operation and maintenance; OPEX = operating expenditures; WSP = waste stabilization pond.

[a] Considered irrelevant and thus not considered here. [b] Not used for scoring.

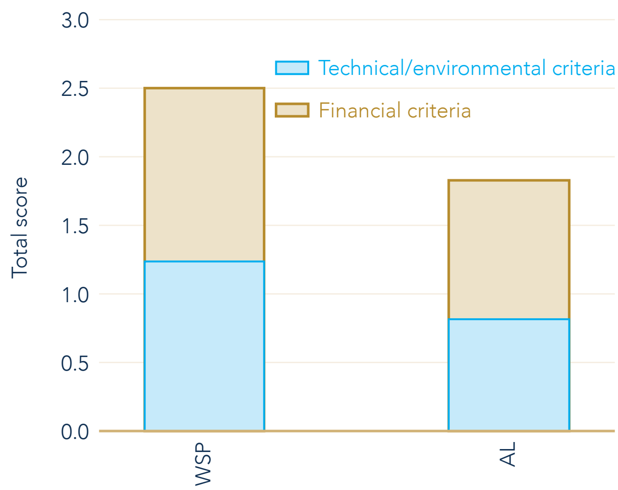
TABLE 6.5
Summary of Weighted Scoring for Remaining Technologies after Step 4 for the Morocco Case

	TECHNICAL/ ENVIRONMENTAL CRITERIA		FINANCIAL CRITERIA		WEIGHTED SCORE		
#	AVERAGE SCORE CRITERIA #1–7	WEIGHT OF CRITERIA #1–7	AVERAGE SCORE CRITERIA #8–9	WEIGHT OF CRITERIA #8–9	CRITERIA #1–7	CRITERIA #8–9	TOTAL
Primary + secondary treatment							
6 WSP	2.50	50%	2.50	50%	1.25	1.25	**2.50**
7 AL	1.67	50%	2.00	50%	0.83	1.00	**1.83**

Note: AL = aerated lagoon; WSP = waste stabilization pond.

FIGURE 6.1

Summary of Weighted Scoring for Remaining Technologies after Step 4 for the Morocco Case



Note: AL = aerated lagoon; WSP = waste stabilization pond.

CONCLUSION

The analysis leads to two potentially suitable technologies for this small town, namely WSP (without an anaerobic pond) and AL, with WSP showing a considerably better score. These two technologies are deemed appropriate for this particular small town and should be further analyzed as the project moves into the next phase.

Decision makers will also need to continue to take into account the potential combinations of technology trains for these two technologies presented in tables 3.5 and 3.6 during the prefeasibility and feasibility phases of the project cycle, for which the relevant rows of the tables are presented here.

			WASTEWATER TREATMENT TRAIN																										
			PRETREATMENT				PRIMARY TREATMENT					SECONDARY TREATMENT														TERTIARY TREATMENT			
OPTION	TECHNOLOGY	ABBREV.	SCREEN	SIEVE	GRIT/FAT REMOVAL	EQUALIZATION	PST	SEPTIC TANK	BIOGAS DIGESTER	IMHOFF TANK	LIQUID/SOLID SEPARATION	ABR	UASB REACTOR	AT	SBR	STONE MEDIA TF	PLASTIC MEDIA TF	RBC	FST	AERATED LAGOON	ANAEROBIC POND	FACULTATIVE POND	MATURATION POND	ANAEROBIC FILTER	PLANTED GRAVEL-FILTER	DISINFECTION–UV	DISINFECTION–CHLORINE	POLISHING POND	ROCK FILTER
Primary + Secondary treatment																													
1	**Waste stabilization pond**	WSP	■		■																■ (as needed)	■	■				▒		▒
2	**Aerated lagoon**	AL	■		■															■								▒	▒

			SLUDGE TREATMENT TRAIN													
OPTION	TECHNOLOGY	ABBREV.	UASB	SEDIMENTATION TANK	GRAVITY THICKENER	MECHANICAL THICKENER	ANAEROBIC DIGESTION	AEROBIC STABILIZATION	POST-THICKENER	MECHANICAL DEWATERING	SLUDGE DRYING BED	SOLAR DRYING	WETLAND	COMPOSTING	SEPTAGE TREATMENT	DIRECT REUSE
Primary + Secondary treatment																
1	**Waste stabilization pond**	WSP									■				▒	
2	**Aerated lagoon**	AL									■				▒	

■ Typical component
▒ Optional component (either additional or replacing another component)

Note: ABR = anaerobic baffled reactor; AT = aeration tank; FST = final sedimentation tank; PST = primary sedimentation tank; RBC = rotating biological contactor; SBR = sequencing batch reactor; TF = trickling filter; UASB = upflow anaerobic sludge blanket reactor; UV = ultraviolet.

Case 2: Small Town in Vietnam

The analysis of this case study follows the general methodology described in chapter 5.

Step 1: Familiarize with GUIDE METHODOLOGY

Decision makers from the utility covering water and sanitation convened and familiarized themselves with the approach.

Step 2: PROJECT CRITERIA

The project criteria described in chapter 4 of the guide were discussed by the decision makers, and table 6.6 was produced to summarize the outcome.

TABLE 6.6
Project Criteria for the Vietnam Case

PROJECT CRITERION	COMMENTS
1. Feasibility of sewer	
Responsibility for water supply and sanitation service delivery	Water and sanitation are handled by the same utility.
Water availability	Water availability is guaranteed. It is estimated that about 99% of the population has access to safe water.
Stormwater management	Sewage and stormwater are managed separately (that is, no combined systems), though there are imperfections in the system and stormwater infiltration can be high.
Solid waste management	Solid waste is collected separately. As is observed in the existing sewer system, solid waste has no relevant negative impacts on the sewer network.
Conclusions	**Sewer system already exists and is working properly.**
2. Total connections to WWTP	
Project horizon	20 years
Residential population	50,000 people
Sewer connection rate	More than 90% of the population is already connected.
Industrial waste streams	Not a major concern, but industries may contribute about 10%–20% of the overall wastewater pollution, which is currently being collected.
Fecal sludge and/or septage	Fecal sludge volumes are low because the majority of the population is already connected to a sewer system.
Urban/industrial growth	An annual growth rate of 2%–3% appears realistic. An average of 2.5% is assumed.
Conclusions	Total future population = ca. 80,000 PE Connected total future population = ca. 75,000 PE Industrial loads = 20% of population = 15,000 PE **Total estimated capacity of WWTP = 90,000 PE**
3. Fecal sludge	
Conclusions (see item 2)	**Fecal sludge is not considered an important factor for the WWTP, even though a septage reception station should be installed.**

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TABLE 6.6

Project Criteria for the Vietnam Case (*Continued*)

PROJECT CRITERION	COMMENTS
4. Regulations for treated discharge and reuse	
Discharge regulations	The quality of treated effluent is regulated in Vietnam through "QCVN 14/2008" (National Technical Regulation on Domestic Wastewater), which distinguishes between wastewater discharges into waters that are either used or not used for water supply. In this case study, the former applies, leading to the following criteria: **BOD_5 ≤ 30 mg/L, ammonium-N ≤ 5 mg/L, nitrate-N ≤ 30 mg/L,** and **total coliforms ≤ 3,000 MPN/100 mL,** among others.
Reuse regulations	Direct reuse of treated wastewater is not envisaged in the foreseeable future.
Conclusions	**Standards for discharge quality require both removal of organic pollution (BOD_5) and oxidation of nitrogen (nitrification). Denitrification (removal of oxidized nitrogen) requirements are weak. In addition, disinfection is required.**
5. Available land for the WWTP	
Land assigned for WWTP	Land is relatively expensive in the vicinity of the small town. Limiting the required WWTP footprint is thus considered to be important.
Elevation	Land is flat, requiring some pumping. Long conveyance distances to the WWTP should be minimized.
Flood protection	There is considerable flooding risk at the possible WWTP sites, requiring special attention in the design phase.
Geotechnical characteristics	Clay soil and alluvial sediments. Heavy structures will require geotechnical surveys and appropriate foundations.
Reserves for later expansion	Feasible, but because of high land prices, such expansions should be limited.
Conclusions	**Suitable land for the WWTP exists but is expensive. Minimization of the WWTP footprint is thus important.**
6. Power supply to the WWTP	
Reliability of electricity	Electricity is available and reliable. Energy cost is not high.
Maximum possible capacity	No particular known limits.
Onsite generation of power	If feasible, this is considered to be an interesting option.
Conclusions	**Electricity from the grid is reliable and not too expensive.**

Note: BOD_5 = five-day biological oxygen demand; PE = population equivalent; WWTP = wastewater treatment plant.

In summary, and using the decision tree presented in figure 5.3 as a guide, Step 2 concludes that (a) this guide is applicable; (b) a sewer system is already in place and its use has been proven; (c) fecal sludge disposal/cotreatment will not be a relevant factor or constraint; (d) wastewater treatment requires very efficient removal of organics, nitrification, and disinfection; (e) land is available but costly; and (f) power supply is good.

Step 3: TECHNOLOGY CRITERIA

The technology criteria described in chapter 4 of the guide were discussed by the decision makers, and table 6.7 was produced to summarize the outcome.

TABLE 6.7

Technology Criteria and Exclusion Criteria for the Vietnam Case

TECHNOLOGY CRITERION	COMMENTS	EXCLUSION OF TECHNOLOGIES?
Treatment efficiency	As described in table 6.6, treatment targets are defined by: ▪ BOD_5 ≤ 30 mg/L; ▪ Ammonium-N ≤ 5 mg/L; ▪ Nitrate-N ≤ 30 mg/L; and ▪ Total coliforms ≤ 3,000 MPN/100 mL.	Comparing the treatment targets with the information provided in chapter 4 "Treatment Efficiency," it becomes clear that only a limited range of technologies can comply with the BOD_5 limit. The only remaining technology options are **CW(1-st), CW(hybrid), EA, SBR(EA), TF, RBC, and UASB-TF**. No technology needs to be excluded because of the total coliforms requirement because all these technologies could be equipped with a separate tertiary disinfection stage. However, tertiary stages, such as **PP, RF, and RDF**, are not needed to achieve the treatment targets with the previously indicated remaining technologies and are hence **excluded.**
Ease of upgrading to enhanced nutrient removal	Decision makers recognized that discharge requirements could become even more stringent in the future.	**Ease of upgrading is to be considered in the technology assessment.**
Land availability	Land is available but expensive.	Technologies **requiring large land areas should be excluded**. In particular, and when considering the information presented in chapter 4 "Land Availability," this means that **WSP, CW(1-st), CW(hybrid), and UASB-WSP** should be **excluded** from further consideration.
Labor qualification	It is assumed that the utility will be able to find and hire qualified personnel, as dictated by the technologies to be selected.	**No technology exclusion is required.**
Availability of replacement parts and O&M inputs	Administrative capacity is sufficient to support operators and provide a regular supply of consumables and spare parts. The town is well connected to major cities, and availability of replacement parts is therefore not a challenge.	**No technology exclusion is required.**
Sludge production	Sludge production is not considered to be a limiting factor.	**No technology exclusion is required.**
Energy use	Reliable and relatively cheap energy supply can be provided.	**No technology exclusion is required.**
OPEX	Is considered important to compare technologies.	**No technology exclusion is required.**

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TABLE 6.7

Technology Criteria and Exclusion Criteria for the Vietnam Case (*Continued*)

TECHNOLOGY CRITERION	COMMENTS	EXCLUSION OF TECHNOLOGIES?
CAPEX	Is considered important to compare technologies.	**No technology exclusion is required.**
Reuse potential	Not of particular relevance, as long as the treated effluents meet the official requirements.	**No technology exclusion is required.**
Climate change impact	Decision makers decided that this criterion may be applied, as deemed appropriate.	**No technology exclusion is required.**
Other	Decision makers also considered the following: ▪ In Vietnam, TFs are not allowed for WWTPs with a capacity beyond 50,000 PE. ▪ It was mutually agreed that the RBC technology is usually employed only for plants smaller than the one in this case.	**TF, UASB-TF, and RBC** are **excluded** from further consideration.

Note: BOD_5 = five-day biological oxygen demand; CW(1-st) = one-stage constructed wetland; CW(hybrid) = hybrid constructed wetland; EA = extended aeration; O&M = operation and maintenance; PE = population equivalent; PP = polishing pond; RBC = rotating biological contactor; RDF = rotary disc filter; RF = rock filter; SBR(EA) = sequencing batch reactor (extended aeration variant); TF = trickling filter; UASB = upflow anaerobic sludge blanket reactor; UASB-TF = UASB followed by a TF; UASB-WSP = UASB followed by a WSP; WSP = waste stabilization pond; WWTP = wastewater treatment plant.

Step 4: NONNEGOTIABLE or EXCLUSION CRITERIA

As described in chapter 5 “Step 4: Identify and Apply Nonnegotiable or Exclusion Criteria,” the decision makers determined which technology criteria were nonnegotiable because of local constraints and priorities and which provide more flexibility. These criteria were marked accordingly in the application of this step and helped to eliminate technologies that did not meet the prior identified requirements.

As most technologies are excluded, only two options will thus be subjected to scoring, namely extended aeration (EA) and sequencing batch reactor (extended aeration variant) (SBR(EA)).

TABLE 6.8

Summary of Excluded Technologies for the Vietnam Case

TECHNOLOGY		TECHNOLOGY CRITERION LEADING TO EXCLUSION											
		4.3.1	4.3.2	4.3.3	4.3.4	4.3.5	4.3.6	4.3.7	4.3.8	4.3.9	4.3.10	4.3.11	4.3.12
#		TREATMENT EFFICIENCY	EASE OF UPGRADING TO BNR	LAND AVAILABILITY	LABOR QUALIFICATION	AVAILABLE PARTS + O&M INPUTS	SLUDGE PRODUCTION	ENERGY USE	OPEX	CAPEX	REUSE POTENTIAL	CLIMATE CHANGE IMPACT	OTHER CRITERIA
Primary treatment (only)													
1	ST	excluded	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
2	BD	excluded	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
3	IMH	excluded	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Primary + secondary treatment													
4	ABR	excluded	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
5	ANF	excluded	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
6	WSP	excluded	OK	excluded	OK	OK	OK	OK	OK	OK	OK	OK	OK
7	AL	excluded	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
8	CW(1-st)	OK	OK	excluded	OK	OK	OK	OK	OK	OK	OK	OK	OK
9	CW(hybrid)	OK	OK	excluded	OK	OK	OK	OK	OK	OK	OK	OK	OK
10	UASB	excluded	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
11	EA	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
12	SBR (EA)	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
13	TF	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
14	RBC	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
15	UASB-WSP	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	excluded
14	RBC	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	excluded
15	UASB-WSP	excluded	OK	excluded	OK	OK	OK	OK	OK	OK	OK	OK	OK
16	UASB-TF	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	excluded
Tertiary treatment (additional)													
17	UV	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
18	CI	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
19	PP	excluded	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
20	RF	excluded	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
21	RDF	excluded	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK

Note: ABR = anaerobic baffled reactor; AL = aerated lagoon; ANF = anaerobic filter; BD = biogas digester; BNR = biological nutrient removal; CAPEX = capital expenditures; Cl = chlorination; CW(1-st) = one-stage constructed wetland; CW(hybrid) = hybrid constructed wetland; EA = extended aeration; IMH = Imhoff tank; O&M = operation and maintenance; OPEX = operating expenditures; PP = polishing pond; RBC = rotating biological contactor; RDF = rotary disc filter; RF = rock filter; SBR(EA) = sequencing batch reactor (extended aeration variant); ST = septic tank; TF = trickling filter; UASB = upflow anaerobic sludge blanket reactor; UASB-TF = UASB followed by a TF; UASB-WSP = UASB followed by a WSP; UV = ultraviolet; WSP = waste stabilization pond.

Step 5: Assign WEIGHTING to technology criteria, calculate TOTAL SCORE for remaining technologies

The scoring employs the standard defaults suggested in this guide in table 5.1 (that is, the suggested scores for each technology and the standard default scores). Likewise, for the weighting applied here, the suggested approach of giving equal weight to the technical/environmental criteria and the financial criteria is used.

Tables 6.9 and 6.10 present the outcome of that scoring and weighting exercise, with 3 continuing to be the maximum achievable score.

TABLE 6.9

Summary of Scoring for Remaining Technologies after Step 4 for the Vietnam Case

TECHNOLOGY	TECHNOLOGY CRITERION										
	4.3.1	4.3.2	4.3.3	4.3.4	4.3.5	4.3.6	4.3.7	4.3.8	4.3.9	4.3.10	4.3.11
#	TREATMENT EFFICIENCY	EASE OF UPGRADING TO BNR	LAND AVAILABILITY	LABOR QUALIFICATION	AVAILABLE PARTS + O&M INPUTS	SLUDGE PRODUCTION	ENERGY USE	OPEX	CAPEX	REUSE POTENTIAL[a]	CLIMATE CHANGE IMPACT[a]
Primary + secondary treatment											
13 EA	3	3	3	1	1	1	1	1	1		
14 SBR (EA)	3	3	3	1	1	1	1	1	1		
Tertiary treatment (additional)											
27 UV	N/A	N/A	3	1	1	N/A	3	3	3		
28 Cl	N/A	N/A	3	1	2	N/A	3	3	3		

Note: BNR = biological nutrient removal; CAPEX = capital expenditures; Cl = chlorination; EA = extended aeration; O&M = operation and maintenance; OPEX = operating expenditures; SBR(EA) = sequencing batch reactor (extended aeration variant); UV = ultraviolet.

[a] Not used for scoring.

TABLE 6.10

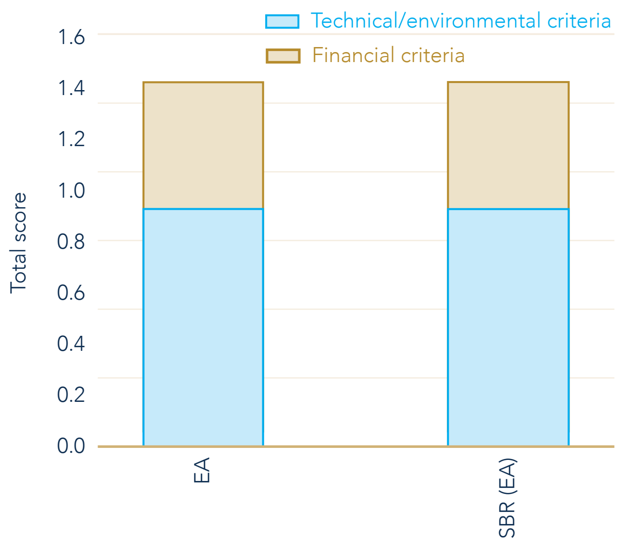
Summary of Weighted Scoring for Remaining Technologies after Step 4 for the Vietnam Case

	TECHNICAL/ ENVIRONMENTAL CRITERIA		FINANCIAL CRITERIA		WEIGHTED SCORE		
#	AVERAGE SCORE CRITERIA #1–7	WEIGHT OF CRITERIA #1–7	AVERAGE SCORE CRITERIA #8–9	WEIGHT OF CRITERIA #8–9	CRITERIA #1–7	CRITERIA #8–9	TOTAL
Primary + secondary treatment							
13 EA	1.86	50%	1.00	50%	0.93	0.50	**1.43**
14 SBR (EA)	1.86	50%	1.00	50%	0.93	0.50	**1.43**

Note: EA = extended aeration; SBR(EA) = sequencing batch reactor (extended aeration variant).

FIGURE 6.2

Summary of Weighted Scoring for Remaining Technologies after Step 4 for the Vietnam Case



Note: EA = extended aeration; SBR(EA) = sequencing batch reactor (extended aeration variant).

CONCLUSION

Because both of these remaining technologies, EA and SBR(EA), received an identical score, it can be anticipated that even a more detailed analysis may not lead to major differences between these two. In such situations, either a decision could be made before bidding or both technologies could be permitted as part of the bidding process.

Decision makers will also need to continue to take into account the potential combinations of technology trains for these two technologies presented in tables 3.5 and 3.6 during the prefeasibility and feasibility phases of the project cycle, for which the relevant rows of the tables are presented here.

			WASTEWATER TREATMENT TRAIN																											
			PRETREATMENT				PRIMARY TREATMENT					SECONDARY TREATMENT														TERTIARY TREATMENT				
OPTION	TECHNOLOGY	ABBREV.	SCREEN	SIEVE	GRIT/FAT REMOVAL	EQUALIZATION	PST	SEPTIC TANK	BIOGAS DIGESTER	IMHOFF TANK	LIQUID/SOLID SEPARATION	ABR	UASB REACTOR	AT	SBR	STONE MEDIA TF	PLASTIC MEDIA TF	RBC	FST	AERATED LAGOON	ANAEROBIC POND	FACULTATIVE POND	MATURATION POND	ANAEROBIC FILTER	PLANTED GRAVEL FILTER	DISINFECTION–UV	DISINFECTION–CHLORINE	POLISHING POND	ROCK FILTER	ROTARY DISC FILTER
Primary + Secondary treatment																														
1	Extended Aeration (AS type)	EA	■		■									■					■							○	○			○
2	Extended Aeration (SBR type)	SBR (EA)	■		■										■											○	○			○

			SLUDGE TREATMENT TRAIN													
OPTION	TECHNOLOGY	ABBREV.	UASB	SEDIMENTATION TANK	GRAVITY THICKENER	MECHANICAL THICKENER	ANAEROBIC DIGESTION	AEROBIC STABILIZATION	POST-THICKENER	MECHANICAL DEWATERING	SLUDGE DRYING BED	SOLAR DRYING	WETLAND	COMPOSTING	SEPTAGE TREATMENT	DIRECT REUSE
Primary + Secondary treatment																
1	Extended Aeration (AS type)	EA														
2	Extended Aeration (SBR type)	SBR (EA)														

■ Typical component
○ Optional component (either additional or replacing another component)

Note: ABR = anaerobic baffled reactor; AT = aeration tank; FST = final sedimentation tank; PST = primary sedimentation tank; RBC = rotating biological contactor; SBR = sequencing batch reactor; TF = trickling filter; UASB = upflow anaerobic sludge blanket reactor; UV = ultraviolet.

To meet the disinfection requirements, it is also to be noted that both technology options will require either UV or chlorination as an additional (tertiary) disinfection stage.

Case 3: Small Town in El Salvador

The analysis of this case study follows the general methodology described in chapter 5.

Step 1: Familiarize with GUIDE METHODOLOGY

Decision makers from the national water supply and sanitation utility convened and familiarized themselves with the approach.

Step 2: PROJECT CRITERIA

The project criteria described in chapter 4 of the guide were discussed by the decision makers, and table 6.11 was produced to summarize the outcome.

TABLE 6.11
Project Criteria for the El Salvador Case

PROJECT CRITERION	COMMENTS
1. Feasibility of sewer	
Responsibility for water supply and sanitation service delivery	Responsibility for water supply and sanitation services lies with the national water supply and sanitation utility ANDA.
Water availability	Water services reach the majority of the population, mostly through the public water network (85%–90%) or via public standposts. Some houses also have private wells. Typical water consumption is about 100 L/capita/day.
Stormwater management	Stormwater is not properly managed. To the extent possible, it is directed toward the nearest *quebrada*, or "ravine."
Solid waste management	Solid waste is poorly managed, with only 50% of solid waste collected throughout the municipality. Trash is often burned in gardens or open areas or left out in the street.
Conclusions	**Sewer system appears feasible**. However, it is to be noted that O&M of the sewer system will most likely experience several issues, such as clogging caused by solid waste or considerably increased flows during rainfall. The WWTP should be able to cope with such conditions.

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TABLE 6.11

Project Criteria for the El Salvador Case *(Continued)*

PROJECT CRITERION	COMMENTS
2. Total connections to WWTP	
Project horizon	20 years
Residential population	17,000 people
Sewer connection rate	The existing sanitation system predominantly consists of onsite installations (mostly latrines, with a limited number of septic tanks) with no proper fecal sludge management. Some individual houses or clusters of houses may have a small local sewer network, which typically discharges into the nearest quebrada. These quebradas are formed by erosion caused by surface runoff and are a typical feature of many municipalities in El Salvador. The depth of such quebradas can range from a few meters to several dozen meters, and as the embankments are usually very steep, it is relatively easy to discharge into them without the risk of backflow. The project wants to do away with these sanitation systems and connect about two-thirds of the population in the town's denser areas to a proper sewer system with centralized wastewater treatment. The remaining one-third of the population will continue using onsite sanitation facilities to be incorporated into a properly managed fecal sludge service chain in the future.
Industrial waste streams	Industrial waste streams are not considered a relevant factor. Only a few family businesses are making a living from agricultural and food processing, which should not contribute in a significant way to the waste streams.
Fecal sludge and/or septage	Fecal sludge and septage are currently not well managed, with a small-scale private sector offering emptying of septic tanks, but there is no clarity of where the waste is being transported and treated. After project implementation, any septage collected should be disposed of and treated at the new WWTP.
Urban/industrial growth	Population growth is relatively high but has been affected by migration to larger cities, particularly to the capital, San Salvador. A growth rate of 1%–2% may be realistic. A growth rate of 1.5% has been assumed.
Conclusions	Total future population = ca. 23,000 PE Connected total future population = ca. 15.000 PE Industrial loads: not relevant About 8,000 PE will continue with onsite sanitation. The majority of those will continue using latrines, which are backfilled once full. Only a limited number of residents will use septic tanks, and the septage volume hauled to the WWTP in future will not be large. **Total estimated capacity of WWTP = 16,000 PE (including a provision of 1,000 PE for septage)**
3. Fecal sludge	
Conclusions (see item 2)	**Possible overloading of the WWTP by fecal sludge is not considered a factor as the expected volumes are not particularly high.**

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TABLE 6.11

Project Criteria for the El Salvador Case *(Continued)*

PROJECT CRITERION	COMMENTS
4. Regulations for treated discharge and reuse	
Discharge regulations	The required treatment standards are set by ANDA's "*Normas Técnicas para Abastecimiento de Agua Potable y Alcantarillados de Aguas Negras.*" This norm requires **BOD_5 ≤ 60 mg/L and SS ≤ 60 mg/L**.
Reuse regulations	Some households have gardens in which graywater is reused for irrigation. Reuse of untreated wastewater for the irrigation of crops is also common.
Conclusions	**Standards for discharge quality are defined by requirements for removal of organic pollution—that is, BOD_5 and SS. Informal reuse for irrigation is common; thus, improved hygienic discharge quality would be an added benefit.**
5. Available land for the WWTP	
Land assigned for WWTP	Space availability is generally low. The only location downstream of the small town that is suitable and available for the WWTP has an area of only about 5,000 m^2.
Elevation	No pumping head is required.
Flood protection	Flooding is not considered an issue.
Geotechnical characteristics	Unknown. Nevertheless, the soil is typically prone to erosion, and heavy structures may thus require proper foundations.
Reserves for later expansion	Expansion is not possible.
Conclusions	**The only suitable land for the WWTP has a very limited footprint. Because no expansion is possible at that site in the future, a small plant footprint is considered even more important.**
6. Power supply to the WWTP	
Reliability of electricity	Electricity coverage is generally good, but power outages do happen. Hence, the lesser dependence on the public grid, the greater the possibility of safe operation.
Maximum possible capacity	Unclear maximum capacity.
Onsite generation of power	Solar generation of power could be an option.
Conclusions	**Electricity supply is good, but outages do happen. Low power consumption is preferred. Solar panels may also be considered.**

Note: ANDA = Administración Nacional de Acueductos y Alcantarillados; BOD_5 = five-day biological oxygen demand; O&M = operation and maintenance; PE = population equivalent; SS = suspended solids; WWTP = wastewater treatment plant.

In summary, and using the decision tree presented in figure 5.3 as a guide, Step 2 concludes that (a) this guide is applicable; (b) a sewer system is feasible; (c) fecal sludge disposal/cotreatment will not be a relevant factor or constraint, though some provision is included for septage in the total estimated capacity of the WWTP; (d) treatment focuses on the removal of organic pollution and (to the extent possible) on improving hygienic quality; (e) land availability is limited; and (f) power consumption should be minimized.

Step 3: TECHNOLOGY CRITERIA

The technology criteria described in chapter 4 of the guide were discussed by the decision makers, and table 6.12 was produced to summarize the outcome.

TABLE 6.12

Technology Criteria and Exclusion Criteria for the El Salvador Case

TECHNOLOGY CRITERION	COMMENTS	EXCLUSION OF TECHNOLOGIES?
Treatment efficiency	As described in the previous table, treatment targets are defined by: • $BOD_5 \leq 60$ mg/L; and • $SS \leq 60$ mg/L.	Comparing the treatment targets with the information provided in chapter 4 "Treatment Efficiency," it becomes clear that only a limited range of technologies can comply with the BOD_5 limit. The only remaining technology options are **CW(1-st), CW(hybrid), EA, SBR(EA), TF, RBC, and UASB-TF**. No technology needs to be excluded because of the hygienic requirements because all those technologies could be equipped with a separate tertiary disinfection stage. However, tertiary stages, such as **PP, RF, and RDF,** are not needed to achieve the treatment targets with the previously indicated remaining technologies and are thus **excluded**.
Ease of upgrading to enhanced nutrient removal	No such future requirements are expected.	**No technology exclusion is required.**
Land availability	Land availability is considered an issue. The only plot available has a footprint of about 5,000 m^2, which relative to the envisaged WWTP capacity of 16,000 cap. equals 0.31 m^2/cap.	Comparing land availability to the information in chapter 4 "Land Availability," it becomes clear that the **CW(1-st) and CW(hybrid)** technology options both need to be **excluded** from further consideration. **WSP and UASB-WSP** should also be **excluded** because of their high land requirements.
Labor qualification	Technical capacity varies, depending on ANDA's involvement in system management, though the number of highly trained staff is limited and concentrated in the larger urban areas. Nevertheless, it is expected that ANDA will be able to find and hire suitably qualified personnel for the selected technologies.	**No technology exclusion is required.**
Availability of replacement parts and O&M inputs	Accessibility to larger urban centers has improved over the years. Despite this, using technologies that minimize the need for replacement parts or O&M inputs may be desirable.	**No technology exclusion is required.**
Sludge production	Most of the sludge may be reused by local farmers in agriculture. Sludge volume is therefore not considered relevant for decision making.	**No technology exclusion is required.**

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TABLE 6.12

Technology Criteria and Exclusion Criteria for the El Salvador Case (*Continued*)

TECHNOLOGY CRITERION	COMMENTS	EXCLUSION OF TECHNOLOGIES?
Energy use	Although electricity supply is not considered a limiting factor for technology selection, low financial capacity may render a lower energy consumption (and therefore costs) desirable.	**No technology exclusion is required.**
OPEX	High OPEX would definitely put a major strain on public finances; thus, low OPEX is preferable. This criterion is considered to be important to compare technologies.	**No technology exclusion is required.**
CAPEX	Similar to OPEX.	**No technology exclusion is required.**
Reuse potential	As mentioned in the project criteria, there is interest in water reuse options for agricultural uses. This requirement is already included in technology criterion 1: treatment efficiency.	**No technology exclusion is required.**
Climate change impact	The information in chapter 4 "Climate Change Impact" states that high GHG emissions are typically associated with high energy consumption and with anaerobic stages. The former dimension is already included in technology criterion 7: energy use and thus does not require further consideration. The decision makers decided that no additional criteria should be applied in this regard.	**No technology exclusion is required.**

Note: ANDA = Administración Nacional de Acueductos y Alcantarillados; BOD_5 = five-day biological oxygen demand; cap = capita; CW(1-st) = one-stage constructed wetland; CW(hybrid) = hybrid constructed wetland; EA = extended aeration; GHG = greenhouse gas; O&M = operation and maintenance; OPEX = operating expenditures; PP = polishing pond; RBC = rotating biological contactor; RDF = rotary disc filter; RF = rock filter; SBR(EA) = sequencing batch reactor (extended aeration variant); SS = suspended solids; TF = trickling filter; UASB = upflow anaerobic sludge blanket reactor; UASB-TF = UASB followed by a TF; UASB-WSP = UASB followed by a WSP; WSP = waste stabilization pond; WWTP = wastewater treatment plant.

Step 4: NONNEGOTIABLE or EXCLUSION CRITERIA

As described in chapter 5 "Step 4: Identify and Apply Nonnegotiable or Exclusion Criteria," the decision makers determined which technology criteria were nonnegotiable because of local constraints and priorities and which provide more flexibility. These criteria were marked accordingly in the application of this step and helped to eliminate technologies that did not meet the prior identified requirements.

Five technologies and two disinfection options remain.

TABLE 6.13

Summary of Excluded Technologies for the El Salvador Case

TECHNOLOGY		TECHNOLOGY CRITERION LEADING TO EXCLUSION										
		4.3.1	4.3.2	4.3.3	4.3.4	4.3.5	4.3.6	4.3.7	4.3.8	4.3.9	4.3.10	4.3.11
#		TREATMENT EFFICIENCY	EASE OF UPGRADING TO BNR	LAND AVAILABILITY	LABOR QUALIFICATION	AVAILABLE PARTS + O&M INPUTS	SLUDGE PRODUCTION	ENERGY USE	OPEX	CAPEX	REUSE POTENTIAL	CLIMATE CHANGE IMPACT
Primary treatment (only)												
1	ST	excluded	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
2	BD	excluded	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
3	IMH	excluded	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Primary + secondary treatment												
4	ABR	excluded	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
5	ANF	excluded	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
6	WSP	excluded	OK	excluded	OK	OK	OK	OK	OK	OK	OK	OK
7	AL	excluded	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
8	CW(1-st)	OK	OK	excluded	OK	OK	OK	OK	OK	OK	OK	OK
9	CW(hybrid)	OK	OK	excluded	OK	OK	OK	OK	OK	OK	OK	OK
10	UASB	excluded	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
11	EA	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
12	SBR (EA)	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
13	TF	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
14	RBC	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
15	UASB-WSP	excluded	OK	excluded	OK	OK	OK	OK	OK	OK	OK	OK
16	UASB-TF	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
Tertiary treatment (additional)												
17	UV	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
18	Cl	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
19	PP	excluded	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
20	RF	excluded	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
21	RDF	excluded	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK

Note: ABR = anaerobic baffled reactor; AL = aerated lagoon; ANF = anaerobic filter; BD = biogas digester; BNR = biological nutrient removal; CAPEX = capital expenditures; Cl = chlorination; CW(1-st) = one-stage constructed wetland; CW(hybrid) = hybrid constructed wetland; EA = extended aeration; IMH = Imhoff tank; O&M = operation and maintenance; OPEX = operating expenditures; PP = polishing pond; RBC = rotating biological contactor; RDF = rotary disc filter; RF = rock filter; SBR(EA) = sequencing batch reactor (extended aeration variant); ST = septic tank; TF = trickling filter; UASB = upflow anaerobic sludge blanket reactor; UASB-TF = UASB followed by a TF; UASB-WSP = UASB followed by a WSP; UV = ultraviolet; WSP = waste stabilization pond.

Step 5: Assign WEIGHTING to technology criteria, calculate TOTAL SCORE for remaining technologies

The scoring employs the standard defaults suggested in this guide in table 5.1 (that is, the suggested scores for each technology and the standard default scores). Likewise, for the weighting applied here, the suggested approach of giving equal weight to the technical/environmental criteria and the financial criteria is used.

Tables 6.14 and 6.15 present the outcome of that scoring and weighting exercise, with 3 continuing to be the maximum achievable score.

TABLE 6.14

Summary of Scoring for Remaining Technologies after Step 4 for the El Salvador Case

TECHNOLOGY		TECHNOLOGY CRITERION										
		4.3.1	4.3.2	4.3.3	4.3.4	4.3.5	4.3.6	4.3.7	4.3.8	4.3.9	4.3.10	4.3.11
#		TREATMENT EFFICIENCY	EASE OF UPGRADING TO BNR	LAND AVAILABILITY	LABOR QUALIFICATION	AVAILABLE PARTS + O&M INPUTS	SLUDGE PRODUCTION	ENERGY USE	OPEX	CAPEX	REUSE POTENTIAL[a]	CLIMATE CHANGE IMPACT[a]
Primary + secondary treatment												
13	EA	3	3	3	1	1	1	1	1	1		
14	SBR (EA)	3	3	3	1	1	1	1	1	1		
15	TF	3	2	3	2	2	1	2	2	1		
16	RBC	3	2	3	2	2	1	2	2	1		
25	UASB-TF	3	2	3	1	2	1	2	2	1		
Tertiary treatment (additional)												
27	UV	N/A	N/A	3	1	1	N/A	3	3	3		
28	CI	N/A	N/A	3	1	2	N/A	3	3	3		

Note: BNR = biological nutrient removal; CAPEX = capital expenditures; CI = chlorination; EA = extended aeration; N/A = not applicable; O&M = operation and maintenance; OPEX = operating expenditures; RBC = rotating biological contactor; SBR(EA) = sequencing batch reactor (extended aeration variant); TF = trickling filter; UASB = upflow anaerobic sludge blanket reactor; UASB-TF = UASB followed by a TF; UV = ultraviolet.

[a] Not used for scoring.

TABLE 6.15

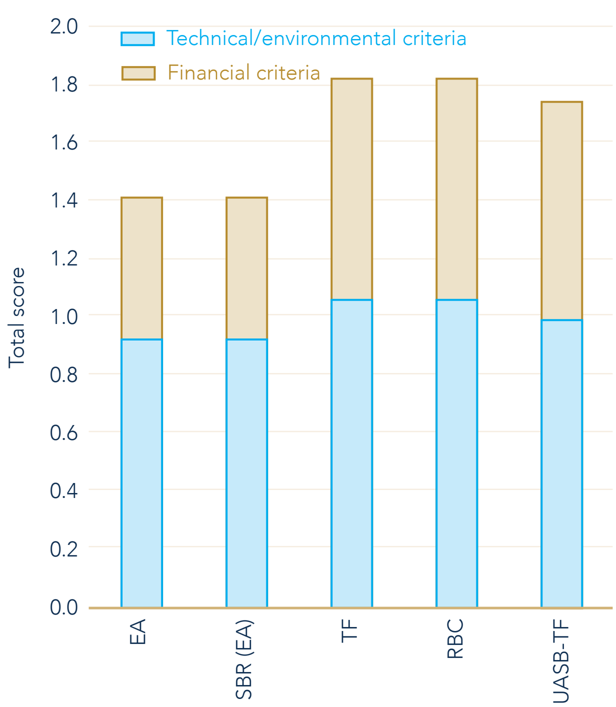
Summary of Weighted Scoring for Remaining Technologies after Step 4 for the El Salvador Case

#	TECHNICAL/ ENVIRONMENTAL CRITERIA		FINANCIAL CRITERIA		WEIGHTED SCORE		
	AVERAGE SCORE CRITERIA #1–7	WEIGHT OF CRITERIA #1–7	AVERAGE SCORE CRITERIA #8–9	WEIGHT OF CRITERIA #8–9	CRITERIA #1–7	CRITERIA #8–9	TOTAL
Primary + secondary treatment							
13 EA	1.86	50%	1.00	50%	0.93	0.50	**1.43**
14 SBR (EA)	1.86	50%	1.00	50%	0.93	0.50	**1.43**
15 TF	2.14	50%	1.50	50%	1.07	0.75	**1.82**
16 RBC	2.14	50%	1.50	50%	1.07	0.75	**1.82**
25 UASB-TF	2.00	50%	1.50	50%	1.00	0.75	**1.75**

Note: EA = extended aeration; RBC = rotating biological contactor; SBR(EA) = sequencing batch reactor (extended aeration variant); TF = trickling filter; UASB = upflow anaerobic sludge blanket reactor; UASB-TF = UASB followed by a TF.

FIGURE 6.3

Summary of Weighted Scoring for Remaining Technologies after Step 4 for the El Salvador Case



Note: EA = extended aeration; RBC = rotating biological contactor; SBR(EA) = sequencing batch reactor (extended aeration variant); TF = trickling filter; UASB = upflow anaerobic sludge blanket reactor; UASB-TF = UASB followed by a TF.

CONCLUSION

The outcome shows considerable differences in the weighted scoring, with EA and SBR(EA) clearly inferior to the other three technology options, mainly for financial reasons. Consequently, it would be recommended to consider only the three best scorers—namely trickling filter (TF), rotating biological contactor (RBC), and upflow anaerobic sludge blanket reactor (UASB)-TF—for further analysis.

Decision makers will also need to continue to take into account the potential combinations of technology trains for these three technologies—as presented in tables 3.5 and 3.6—during the prefeasibility and feasibility phases of the project cycle, for which the relevant rows of the tables are presented here.

			WASTEWATER TREATMENT TRAIN																											
			PRETREATMENT				PRIMARY TREATMENT					SECONDARY TREATMENT														TERTIARY TREATMENT				
OPTION	TECHNOLOGY	ABBREV.	SCREEN	SIEVE	GRIT/FAT REMOVAL	EQUALIZATION	PST	SEPTIC TANK	BIOGAS DIGESTER	IMHOFF TANK	LIQUID/SOLID SEPARATION	ABR	UASB REACTOR	AT	SBR	STONE MEDIA TF	PLASTIC MEDIA TF	RBC	FST	AERATED LAGOON	ANAEROBIC POND	FACULTATIVE POND	MATURATION POND	ANAEROBIC FILTER	PLANTED GRAVEL FILTER	DISINFECTION–UV	DISINFECTION–CHLORINE	POLISHING POND	ROCK FILTER	ROTARY DISC FILTER
Primary + Secondary treatment																														
1	**Trickling Filter**	TF	●		●		●			●		○				○	●		●							○	○			
2	**Rotating Biological Contractor**	RBC	●		●			●		○		○						●	●							○	○			
3	**UASB-TF**	UASB-TF	●	●	●								●			○	●		●							○	○			

			SLUDGE TREATMENT TRAIN												
OPTION	TECHNOLOGY	ABBREV.	UASB	SEDIMENTATION TANK	GRAVITY THICKENER	MECHANICAL THICKENER	ANAEROBIC DIGESTION	AEROBIC STABILIZATION	POST-THICKENER	MECHANICAL DEWATERING	SLUDGE DRYING BED	SOLAR DRYING	WETLAND	COMPOSTING	SEPTAGE TREATMENT	DIRECT REUSE
Primary + Secondary treatment															
1	**Trickling Filter**	TF														
2	**Rotating Biological Contractor**	RBC														
3	**UASB-TF**	UASB-TF														

● Typical component
○ Optional component (either additional or replacing another component)

Note: ABR = anaerobic baffled reactor; AT = aeration tank; FST = final sedimentation tank; PST = primary sedimentation tank; RBC = rotating biological contactor; SBR = sequencing batch reactor; TF = trickling filter; UASB = upflow anaerobic sludge blanket reactor; UV = ultraviolet.

To meet the reuse requirements, it may be noted that TF, RBC, and UASB-TF will require an additional (tertiary) disinfection stage, such as chlorination or UV.

Appendix A: Extended Aeration versus Conventional Activated Sludge

Issues with the CAS Process

The conventional activated sludge (CAS) process is built around the idea that the total reactor volume should be minimized, and despite the fact that CAS is one of the most energy intensive of wastewater treatment technologies, energy consumption should nevertheless be reduced along the wastewater treatment train. This, however, comes at a price: capital expenditures (CAPEX) associated with electromechanical equipment increase, even if CAPEX associated with civil works decrease to minimize reactor volume. This brings about an increased dependence on control and automation systems, more challenging maintenance requirements, and the need to establish the capacity for swift repairs and to ensure efficient spare part management and procurement. These factors increase the complexity of plant operation and point to the basic need for efficient administration and skilled operators.

CAS systems generate two types of sludge, namely fresh sludge from the primary sedimentation tanks and waste-activated sludge from the aeration tanks. Both require stabilization to minimize the emission of bad odors during disposal or reuse. To that end, CAS usually employs anaerobic sludge digesters, which are expensive to build and difficult to operate. Anaerobic digesters indeed require large volumes, and in low- and middle-income country (LMIC) contexts, about one-third of their total cost is associated with the electromechanical installations required both within and outside the digesters. In LMICs where the equipment often has a relatively higher price than the civil works, the electromechanical components can amount to more than 50 percent of the total digester cost. In addition, digesters are considered risky because methane is produced during sludge digestion, which has caused several explosion incidents at wastewater treatment plants (WWTPs) worldwide, including in high-income countries. Digester operation thus requires skilled operators and well-established procedures for preventive maintenance. Finally, it is important to underscore that the financial/economic assessment of CAS systems almost always seeks to take advantage of the potential for the conversion of the generated methane into electric energy—but such systems require high operation and maintenance (O&M) skill levels. Thus, they will make financial/economic sense only in situations in which energy unit costs are high and/or in which carbon credits for reducing greenhouse gas emissions can be leveraged.

However, most of these conditions are typically not found in small-town settings of LMICs. Consequently, the CAS process—or at least key components of its treatment train—frequently fails in such environments. In fact, a WWTP using the CAS process but with malfunctioning digesters is associated with odor-related issues and complaints by neighbors and operators, so it can pose a severe risk to the plant's security. In addition, if the digestion is not working properly, a domino effect can set in: The sludge volume after digestion will be higher than designed, often overwhelming the complete downstream sludge treatment train. This in turn leads to even poorer dewatering results, further increasing the dewatered sludge volume. Eventually, it may become difficult for the landfill operator to accept sludge volumes that are larger than expected and that are of inferior quality, and the plant operator will be forced to remove insufficient quantities of sludge from the wastewater treatment train. Consequences of such scenarios include an increase in the mixed liquor suspended solids (MLSS), increased energy consumption, and a deterioration in effluent quality. In summary, the CAS process at medium-sized plants implies CAPEX figures that are comparable with those of many other advanced technologies, such as extended aeration (EA), trickling filters (TF), and so on, but it also comes with serious risks associated with unsuccessful O&M, increased operating expenditures (OPEX),[1] and noncompliant effluent quality. Such scenarios are in fact rather frequent.

EA-Activated Sludge Systems

Contrary to CAS, the EA alternative is simpler in that (a) it is not preceded by primary sedimentation tanks, and (b) as the waste-activated sludge is subjected to long retention times in the aeration tanks, no digesters are required to stabilize the sludge. Sizing of the aeration tank volume ensures that the sludge stays sufficiently long in the aerobic zones so that it can be considered stabilized (represented by a high aerobic sludge age or low food to microorganism [F/M] ratios). Separate sludge digesters are therefore not needed. Because of a larger total reactor volume (as compared with CAS), CAPEX figures associated with the EA wastewater treatment train thus tend to increase, but the CAPEX figures associated with the sludge treatment train are lower than those of CAS. In terms of total life-cycle costs, EA usually comes out equal to or more attractive than CAS for small and medium-sized WWTPs. In many LMICs, the breakpoint at which CAS becomes more financially attractive than EA is associated with WWTPs designed for 100,000 to 500,000 population equivalents (PE). Only in high-income countries can this threshold be set lower than 100,000 PE.

For small-town WWTPs, the aforementioned factors—namely, financial costs, ease of operation, reduced safety risks, less problematic sludge disposal, and improved effluent quality compliance—all point toward favoring EA rather than CAS. Consequently, CAS has been excluded from this guide at the preselection stage (see table 3.3), whereas EA remains one of the technologies considered to be appropriate by the guide.

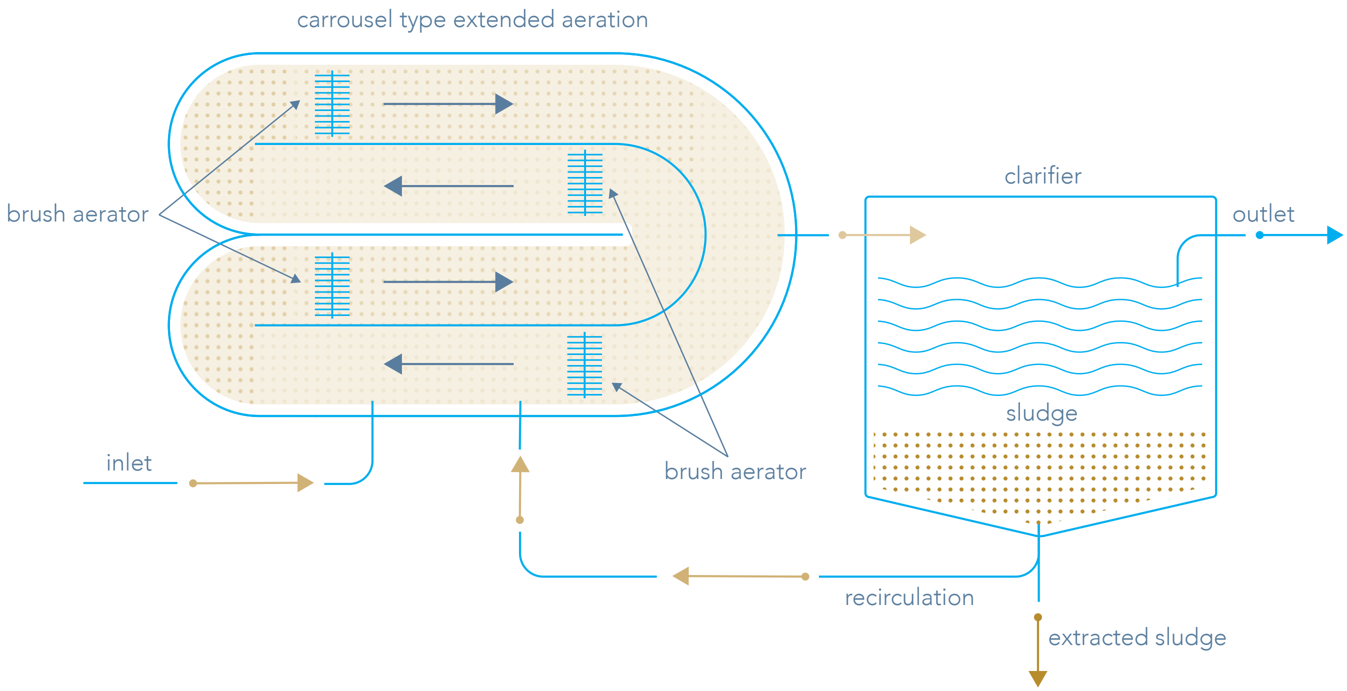
EA systems can be grouped into two fundamentally different flow regimes: (a) flow-through and (b) batch-wise treatment variations. The most common configurations are as follows:

Flow-through

- *Oxidation ditch EA:* In this configuration, the aeration tank is constructed as a closed-loop channel, leading to what are called completely mixed flow conditions. Water depth is only typically in the order of 2 meters, thus enabling the use of horizontal shaft mechanical aerator brushes or similar installations. Vertical shaft aerators can also sometimes be used and are located at the turning points toward the end of the loops. In general, aerators in oxidation ditches not only provide the necessary oxygen for microorganisms but also provide horizontal

FIGURE A1.1

Schematic Diagram of an Oxidation Ditch EA



thrust to facilitate constant movement and mixing of the wastewater-sludge mixture, thereby avoiding settlement of the sludge MLSS.

- *Carrousel type EA:* The tank configuration of carrousel plants is a further development of oxidation ditches, typically employed for larger WWTPs. Instead of a single closed-loop channel (with two 180-degree turning points, one at each end of the system), carrousel facilities typically use tanks with four turning points, before the loops are closed. Water depth is also often increased to 5 meters or more. To increase the low-energy efficiency of mechanical surface aerators, the aeration system can be changed to a pressurized one at the bottom of the tank, but in such cases, horizontal flow thrust needs to be introduced by the use of special mixers.
- *Plug-flow type EA:* In this configuration, tanks are shaped so that flow enters one end and leaves at the other (providing longitudinal flow or plug-flow conditions). This is mostly done to improve efficiency, given that pressurized aeration is used; water depth is increased to 5 to 6 meters; aerated zones and nonaerated zones are installed intermittently[2] with high initial substrate concentrations, allowing for faster biological reaction rates; and smart automation systems for the control of air supply are introduced, complete with effluent quality control sensors and frequency-controlled blowers.

Batch-wise treatment

- *Sequencing batch reactor (SBR) type EA:* This configuration employs batch-wise treatment of the wastewater. In its classical variation, there are at least two parallel SBR tanks, where one tank receives fresh flow (filling and treatment), and in the second tank sludge is settled and the supernatant is withdrawn and discharged (sedimentation and discharge). After some time, following a timed program, the two tanks switch roles: The second tank receives fresh flow, and

FIGURE A1.2

Schematic Diagram of a Carrousel Type EA

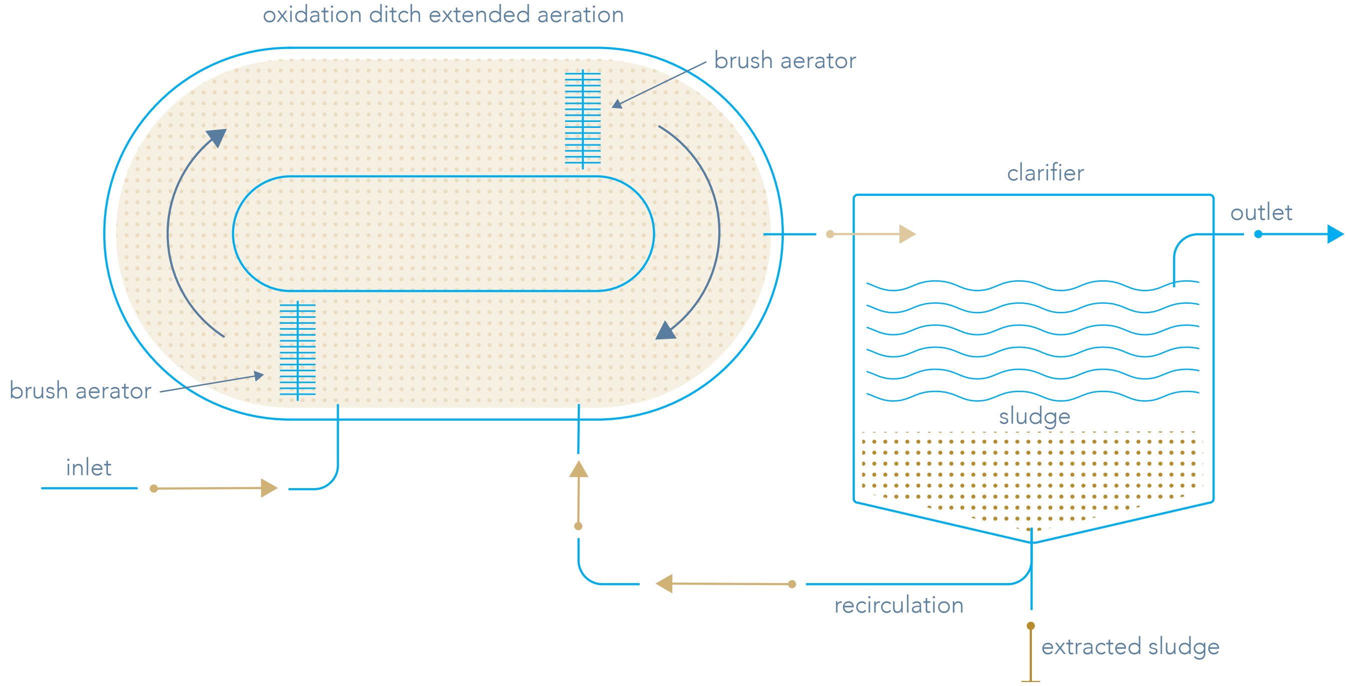
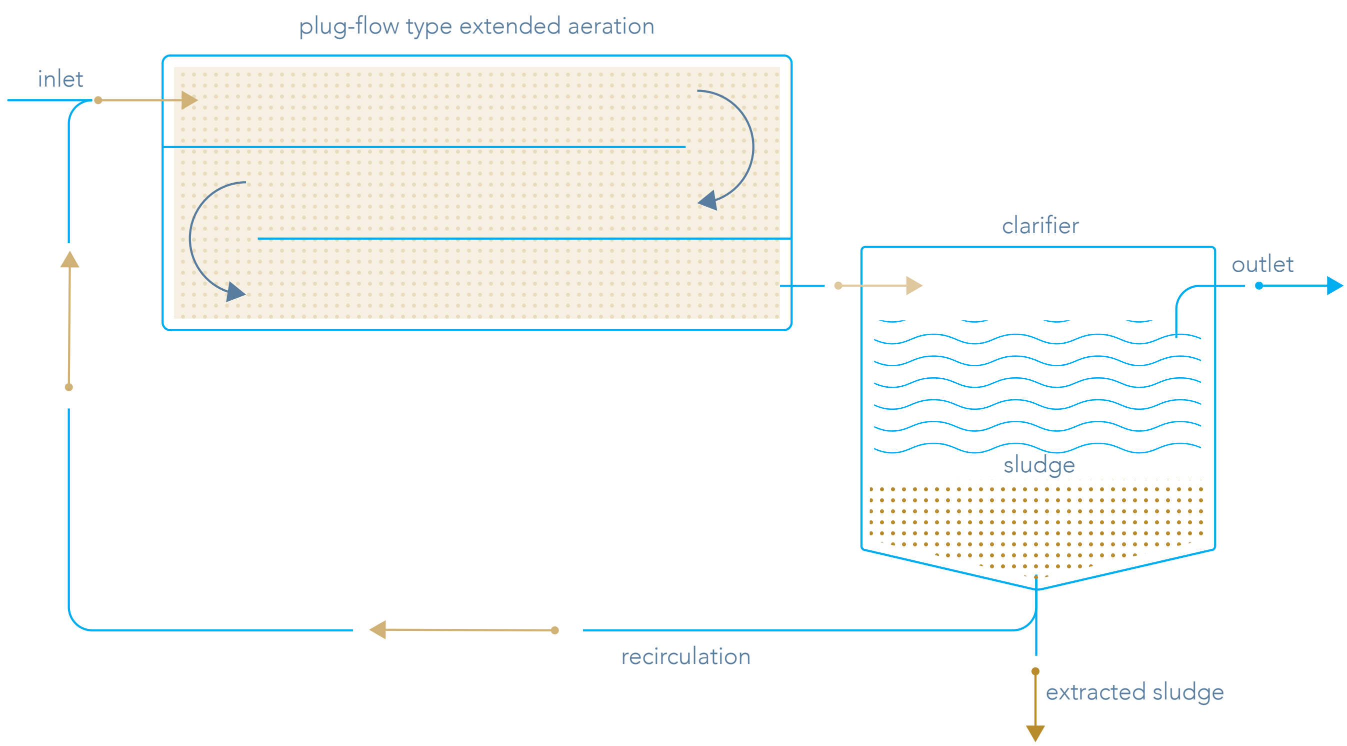


FIGURE A1.3

Schematic Diagram of a Plug-Flow Type EA



the first one transitions to the sedimentation and discharge mode. Although the flow pattern changes over the course of its operation, the biological principles in the SBR remain identical to the other EA configurations described earlier. The key difference lies in the fact that the aeration and the sedimentation take place in the same tank, allowing for the elimination of the piped interconnections between the aeration tanks and the final sedimentation tanks, as well as for the piping for the return sludge pumping. In addition, the overall WWTP footprint can be reduced as rectangular tanks closely aligned to one another can be used, and the classical traveling bridges in the final sedimentation tanks are no longer needed. Modern SBR systems also focus on efficiency, employing 5- to 6-meter-deep tanks and optimized aeration systems. In summary, SBR type EA systems present slightly lower CAPEX figures when compared with the other EA variations described earlier, whereas OPEX figures are comparable to those of optimized completely mixed or plug-flow EA types.

Conclusions

- This guide does not consider CAS to be appropriate for small-town WWTPs: It comes with no CAPEX advantages when compared with EA in a small-town context and poses serious O&M challenges, potentially leading to process failures. Such failures usually start with the malfunctioning of the digester, leading to odor issues, increased sludge volumes, increased OPEX, problems with sludge disposal/reuse, and noncompliant effluent quality, not to mention potential complaints from nearby populations and the plant operators.
- EA is a simpler form of activated sludge that may be suited for certain small-town WWTPs. In this guide, two different variations of EA are presented: (a) EA representing the flow-through configurations and (b) SBR(EA) representing the batch-wise treatment configurations.

Notes

1. OPEX may increase for various reasons: (a) high maintenance/repair costs associated with electromechanical installations; (b) inefficient digestion processes increasing the demand (and costs) in polymers for sludge dewatering; (c) inefficient digestion processes leading to higher sludge volumes and thus higher sludge disposal costs; and (d) inefficient digestion processes producing little or no biogas—therefore, electricity has to be purchased fully from the grid to satisfy the WWTP's needs.
2. Operating in an intermittent aeration mode allows for an improved nutrient effluent quality while minimizing OPEX associated with energy consumption.

References

Andreoli, C. V., Von Sperling, M., and Fernandes, F. 2007. *Sludge Treatment and Disposal*. Vol. 6 of *Biological Wastewater Treatment Series.* London: IWA Publishing.

ARAconsult. 2018. "Evaluation of Sewage Treatment Options Meeting New Indian Standards." Technical Study, financed by KfW. 134. September.

Black & Veatch Corporation. 2010. "Chapter 6 – Disinfection of Wastewater." In *White's Handbook of Chlorination and Alternative Disinfectants*. 5th ed. Hoboken: John Wiley & Sons.

de Lemos Chernicharo, C. A. 2007. *Anaerobic Reactors*. Biological Wastewater Treatment Series, Vol. 4. London: IWA.

Dotro G., Langergraber G., Molle P., Nivala J., Puigagut J., Stein O., and Sperling M. 2017. *Treatment Wetlands*. Biological Wastewater Treatment Series, Vol. 7. London: IWA.

Economic Consulting Associates. 2015. *Strengthening Public Institutions in Engaging and Regulating Domestic Private Sector the Provision of Water and Sanitation Services in Rural Growth Areas and Small Towns: Best Practice Report*. London.

Enerhall, C., and Stenmark, S. 2012. "Disc Filters to Reduce Wastewater Pathogen Levels in Raw Water Sources: Risk Reduction Potential for Göta älv." Master of Science Thesis 2012:54, Department of Civil and Environmental Engineering, Chalmers University, Göteborg, Sweden.

ESMAP (Energy Sector Management Assistance Program). 2012. "A Primer on Energy Efficiency for Municipal Water and Wastewater Utilities." World Bank, Washington, DC.

Golla, Georges. 2014. "Définition d'un Outil d'Évaluation des Technologies Non Conventionnelles de Traitement d'Eaux Usées." Unpublished Report.

Helmer, R., Hespanhol, I., and World Health Organization. 1997. *Water Pollution Control: A Guide to the Use of Water Quality Management Principles*. New York: E & FN Spon.

Jimenez, B., Mara, D., Carr, R., and Brissaud, F. 2010. *Wastewater Treatment for Pathogen Removal and Nutrient Conservation: Suitable Systems for Use in Developing Countries,* IWMI Books, Report H042608. International Water Management Institute, Colombo (Sri Lanka).

Jiménez, B., Maya, C., and Galván, M. 2007. "Helminth Ova Control in Wastewater and Sludge for Advanced and Conventional Sanitation." *Water Science and Technology* 56 (5): 43–51.

Kalogo, Y., and Monteith, H. D. 2008. *State of Science Report: Energy and Resource Recovery from Sludge*. For the Global Water Research Coalition (GWRC), Water Environment Research Foundation (WERF), Alexandria (USA).

Kennedy-Walker, R., Mehta, N., Thomas, S., and Gambrill, M. 2020. "Connecting the Unconnected. Approaches for Getting Households to Connect to Sewerage Networks." World Bank, Washington, DC.

LAS (League of Arab States), ESCWA (United Nations Economic and Social Commission for Western Asia), and ACWUA (Arab Countries Water Utilities Association). 2016. *MDG+ Initiative Second Report 2016*. Amman, Jordan.

Metcalf & Eddy and Aecom. 2014. *Wastewater Engineering, Treatment and Resource Recovery*. 5th edition. New York: McGraw-Hill.

Oakley, S., and Mihelcic, J. R. 2019. "Pathogen Reduction and Survival in Complete Treatment Works." In *Water and Sanitation for the 21st Century: Health and Microbiological Aspects of Excreta and Wastewater Management (Global Water Pathogen Project)*, edited by J. B. Rose and B. Jiménez-Cisneros. Lansing, MI: Michigan State University, MI UNESCO.

Rebhun, M., Heller-Grossman, L., and Manka, J. 1997. "Formation of Disinfection Byproducts during Chlorination of Secondary Effluent and Renovated Water." *Water Environment Research* 69: 1154–62.

Rodriguez, D.J., Serrano, H.A., Delgado, A., Nolasco, D., Saltiel, G. 2020. "From Waste to Resource: Shifting paradigms for smarter wastewater interventions in Latin America and the Caribbean." World Bank, Washington, DC.

"Science for Environment Policy." 2018. European Commission DG Environment News Alert Service, Issue 514, edited by SCU, The University of the West of England, Bristol.

Tilley, E., Ulrich, L., Lüthi, C., Reymond, Ph., Schertenleib, R., and Zurbrügg, C. 2014. *Compendium of Sanitation Systems and Technologies*. 2nd rev. ed. Dübendorf, Switzerland: Swiss Federal Institute of Aquatic Science and Technology (Eawag).

UNESCO World Water Assessment Programme. 2017. *The United Nations World Water Development Report 2017*: *Wastewater: The Untapped Resource.* Paris.

Vazquez Alvarez, V., and Buchauer, K. 2014. "East Asia and Pacific: Wastewater to Energy Processes: A Technical Note for Utility Managers in EAP Countries." World Bank, Washington, DC.

WHO (World Health Organization). 2006. "Volume 4: Excreta and Greywater Use in Agriculture." In *Guidelines for the Safe Use of Wastewater, Excreta and Greywater*. Geneva, Switzerland: WHO.

WHO (World Health Organization) and UNESCO (United Nations Children's Fund). 2017. *Progress on Drinking Water, Sanitation and Hygiene: 2017 Update and SDG Baselines*. Geneva.

World Bank. 2020. "Resilient Water Infrastructure Design Brief." Washington, DC. https://elibrary.worldbank.org/doi/epdf/10.1596/34448.

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