Sanitation for Unserved Populations: Technologies, Implementation Challenges, and Opportunities

Kara L. Nelson¹ and Ashley Murray²

¹Department of Civil and Environmental Engineering and ²Energy and Resources Group, University of California, Berkeley, California 94720; email: nelson@ce.berkeley.edu, amurray@ce.berkeley.edu

Abstract

The global population without complete sanitation services is enormous; it includes those without access to basic, household-level sanitation (2.6 billion) as well as those without adequate collection, treatment, and disposal or reuse of their waste. The main goals of a complete sanitation system are to protect human health and the environment and to recover valuable resources from waste (e.g., water, nutrients, energy). The needs of households and the larger community vary dramatically among the unserved population, as do the financial and institutional resources available to provide sanitation services. Thus, a wide range of technologies is needed that can be adapted to each particular situation. In this chapter, existing sanitation technologies are reviewed, from simple latrines to advanced wastewater treatment, with specific attention to characteristics that affect long-term performance. In addition, the context in which sanitation projects are implemented is discussed, including user preferences and demand, costs and financing, and institutional capacity.

Key Words

evergreen sanitation, Millennium Development Goals, water reuse, wastewater treatment
1. INTRODUCTION

More than 2.6 billion people do not have access to improved sanitation (1). This staggering number still vastly underestimates the true unserved population, as many are provided with very poor services. Furthermore, the number does not include households that are connected to a sewer system, but whose wastewater is discharged directly to the environment without any treatment. The best available statistics suggest that less than 15% of wastewater that is collected receives any treatment before being discharged (2). Although inadequate sanitation is a global phenomenon, the vast majority of the unserved live in South Asia, East Asia, and sub-Saharan Africa, representing 36%, 29%, and 17% of the unserved populations, respectively (3).

Inadequate sanitation has far-reaching implications for public health, the environment, and the global economy: 1.8 million people, mostly children under five, die every year from diarrheal disease (4); many rivers around the world have been turned into virtual sewage canals as every day more than two million tons of human waste are dumped into fresh water bodies (5); and inadequate drinking water and sanitation are estimated to cause more than $750 million in adult productivity losses annually (3). Water pollution resulting from inadequate sanitation is recognized as an integral part the global water crisis, as more and more water bodies become unable to support key functions (e.g., water supply, aquatic habitat) and economic activities (e.g., fisheries, tourism) (6, 7).

To meet the UN Millennium Development Goal (MDG) of reducing the unserved population by 50% by 2015 (1990 baseline), an additional 1.6 billion people (including estimated population growth) must be provided with basic sanitation between 2005 and 2015 (8), or 95,000 households per day (9). Progress is not keeping pace with this quota; the target shortfall is projected to be 550 million people (10). As stated above, these figures only account for basic sanitation and not the provision of wastewater treatment.

The slow expansion of sanitation coverage is not for lack of attention. The importance of adequate sanitation has been recognized in numerous ways, most recently by the UN General Assembly, which designated 2008 as “The International Year of Sanitation.” However, aligning sanitation technologies that are effective,
acceptable to users, and locally affordable with institutions that have the capacity to manage all components of the sanitation scheme is an enormous challenge.

The goals of this chapter are to (a) review the wide range of technical options available for providing sanitation and (b) discuss the technology options within the context in which sanitation projects are implemented. The review of technologies is intended to be as broad as possible, such that the strengths, weaknesses, and trade-offs of various technology choices are apparent. We discuss the institutional, financial, and social factors that impact technology decisions to provide those working on sanitation from multiple disciplines with a common ground for understanding the complex, myriad factors that must be addressed to successfully meet the sanitation challenge.

2. DEFINITION AND GOALS OF SANITATION PROVISION

For the purposes of this paper, we define sanitation as the complete set of components that results in comprehensive management of human excreta and greywater (11–13). This definition is much broader than that used by the Joint Monitoring Program to assess progress toward the MDGs (1). A complete sanitation system should include the following components:

1. A safe, convenient, and hygienic environment for urination and defecation:
   a. Squatting platform or pedestal seat; optional urinal
   b. Method for anal cleansing
   c. Superstructure (safe, well lit, ventilated to prevent odors, aesthetic)
   d. Place for handwashing

2. Collection and treatment of waste material, which may occur either on-site or via transport to a centralized facility

3. Disposal or preferably reuse of treated material

4. Collection, treatment, and disposal or reuse of greywater

To ensure adequate operation and maintenance (O&M), decisions about the physical infrastructure should reflect user preferences, budget constraints, and local technical capacity. Accountable institutions must also be in place to provide management of all system components.

The main goals of a complete sanitation system are to protect human health and the environment and to recover valuable resources from waste (e.g., water, nutrients, energy) (13). Improvement in health at the household level resulting from sanitation interventions (e.g., provision of latrines) has been documented, decreasing the incidence of diarrhea by 32% on average (14). The entire community, as well as downstream populations, must also be protected from discharge of untreated wastes. In Salvador, Brazil, increasing sewerage coverage from 26% to 80% of the households reduced diarrhea in children under three by 22% (15). Thus, complete sanitation can improve health in both the private and public domains. Among the objectives of current sanitation projects, protection of human health is often emphasized, or is the sole goal. However, the environmental impacts of discharging untreated, or inadequately treated, wastes can have detrimental impacts on ecosystem services, as well as water quality and potable water supply. Designing sanitation projects for resource recovery can reduce costs and increase benefits. For example, wastewater contains embodied energy that can be harnessed through anaerobic digestion to produce methane. Wastewater can also provide a reliable source of irrigation and nutrients for crops.

In addition to protecting human health and the environment and enabling resource recovery, a complete sanitation system can help to meet other objectives, such as economic development, water and food security, compliance with water quality standards, and other development goals established by local, national, or international entities.

3. WATER QUALITY STANDARDS AND MONITORING

Appropriate water quality standards are essential to guide the design of sanitation
infrastructure, and a feedback loop is needed between ongoing monitoring and decision making. Enforcement is required to ensure that sanitation projects achieve their intended goals of human and environmental health protection. A common challenge in developing countries is that water quality data are scarce and of poor quality and thus do not provide adequate information for making decisions or assessing complex situations (6). Water quality considerations should be an integral part of national water policies, but in developing countries, this is not usually the case (6). The establishment of water quality regulations and monitoring capacity should be recognized as critical to the implementation of well-targeted sanitation programs and must be addressed at the national level in the context of water policy legislation, regulation, and oversight.

Several types of water quality standards are relevant to sanitation. Standards are needed for (a) treatment plant effluents, depending on whether they are discharged to the environment or reused; (b) the direct disposal or reuse of excreta and greywater; and (c) the beneficial use of treated sludges. For on-site sanitation, design standards should prevent groundwater contamination. In many cases, concentrated wastewater effluents from industries should be pretreated or treated separately from domestic wastewaters. Establishing appropriate standards requires information (including water quality data) about the surface and ground waters that receive the wastes, and ongoing monitoring is needed to determine when degradation has occurred. Allowable discharge levels of pollutants should ideally be based on the assimilative capacity of the receiving water body. Approaches that can be used in the development of water quality standards include risk assessment (16), total maximum daily loads (17, 18), and biomonitoring (19).

Because of the complexity of aquatic ecosystems, a comprehensive approach to setting water quality standards and monitoring is rarely taken. In industrialized countries, most water quality and wastewater effluent standards, particularly for discharge into water bodies, have been developed on the basis of what is technologically and economically feasible. In some cases, the resulting standards may be overly protective, whereas in other cases they are not protective enough (20). In low-income countries, what is technologically and economically feasible may be quite different than in industrialized countries. Setting standards that are too high can hamper the expansion of wastewater treatment plants and/or render effluent requirements unenforceable (11, 20, 21). Where financing is a barrier to building wastewater treatment facilities, incremental progress is preferable to waiting until funds are available for a treatment train that will meet local effluent standards. Allowing for a grace period in meeting effluent standards can enable treatment plants to be built in phases, beginning with primary treatment and expanding as can be afforded (20).

4. OVERVIEW OF TECHNOLOGIES

In this section, we review a wide range of technologies that can be used to collect, transport, and treat human wastes (the complete set of components of a sanitation system were discussed in Section 2). The review is not comprehensive but aims to provide both engineers and nonengineers with a sufficient understanding of the main types of options such that the strengths, weaknesses, and trade-offs of the various technology choices are apparent. Much more detailed information should be sought to inform the actual design process [e.g., (21–25)]. Unfortunately, engineering programs do not often teach such a broad range of options, so many engineers are not aware of key technologies that are suitable for low-income communities. Waste characteristics may also be quite different in developing compared to industrialized countries; for example, wastewater may be more concentrated owing to lower water consumption and may contain higher levels and a wider range of pathogens. Table 1 provides a summary of key constituents in human excreta.
Table 1  Constituents in human waste and wastewater and summary of treatment options

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Public health risk</th>
<th>Environmental health risk</th>
<th>Treatment options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suspended solids</td>
<td>Suspended solids (SS) comprise the organic and inorganic constituents that are suspended (not dissolved) in the wastewater. Their discharge inhibits light penetration into surface waters and can lead to sludge deposits and anaerobic conditions.</td>
<td></td>
<td>X</td>
<td>SS are removed by sedimentation either on-site (e.g., pit latrine, septic tanks) or in a centralized treatment plant (e.g., natural treatment systems, primary sedimentation).</td>
</tr>
<tr>
<td>Biochemical oxygen demand</td>
<td>Biochemical oxygen demand (BOD) is a measure of the amount of oxygen required to biologically degrade the organic matter over a given time period. Discharge of BOD can lead to a decrease of oxygen in surface waters so that aquatic organisms cannot survive.</td>
<td></td>
<td>X</td>
<td>Particulate BOD is removed by the same methods as SS. Soluble (dissolved) BOD is removed by biological degradation, either on-site (e.g., leachfield, composting) or in a centralized treatment plant (e.g., natural treatment systems, biological secondary treatment).</td>
</tr>
<tr>
<td>Chemical oxygen demand</td>
<td>Chemical oxygen demand (COD) is a measure of the amount of oxygen required to completely oxidize the organic matter. The value is higher than BOD because more compounds can be chemically oxidized than biologically oxidized.</td>
<td></td>
<td>X</td>
<td>Treatment to remove BOD removes a large fraction of COD. Removal of the nonbiodegradable COD fraction is typically required only for reuse applications with stringent water quality needs and can be achieved with tertiary treatment (e.g., membranes, advanced oxidation).</td>
</tr>
<tr>
<td>Nutrients</td>
<td>Nitrogen and phosphorus are limiting factors in the growth of algae and plants in most surface waters. Their discharge can cause eutrophication. Nitrogen is present in raw wastewater as urea and organic nitrogen. It can be converted to ammonia, nitrate, and nitrogen gas. Nitrate can also cause methaemoglobinaemia (blue-baby syndrome) in infants. Phosphorus is present in wastewater as inorganic and organic phosphorus.</td>
<td>X</td>
<td>X</td>
<td>Some nutrient removal occurs in natural treatment systems, as well as primary and secondary mechanical treatment. However, advanced biological secondary treatment or chemical precipitation (phosphorus only) is needed to decrease levels sufficiently to prevent eutrophication in most surface waters. Treatment of latrine and septic tank discharges by the soil is often inadequate to prevent contamination of groundwater. An alternative to treatment is to reuse the human waste or wastewater (e.g., agricultural or landscape irrigation), so that the nutrients are assimilated by plants.</td>
</tr>
</tbody>
</table>

(Continued)
Table 1 (Continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Public health risk</th>
<th>Environmental health risk</th>
<th>Treatment options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pathogens</td>
<td>There are four classes of human pathogens (disease-causing organisms) in wastewater: viruses (20–100 nm); bacteria (0.5–2 μm); protozoa (3–20 μm); helminths (20–100 μm)</td>
<td>X</td>
<td>Pathogens may be either removed or inactivated. Removal can occur by physical processes such as settling or filtration. Inactivation can occur either in natural systems, or by disinfection.</td>
<td></td>
</tr>
<tr>
<td>Heavy metals</td>
<td>Heavy metals, such as lead (Pb), cadmium (Cd), nickel (Ni), and copper (Cu) are mostly present in wastewater owing to discharges by businesses and industry. They can be toxic to humans and the environment.</td>
<td>X</td>
<td>Heavy metals are difficult to remove by wastewater treatment. Source control is the best strategy, i.e., decreasing use, and requiring businesses and industry to treat their wastewater on-site, before disposal, reuse, or discharge to the sewer.</td>
<td></td>
</tr>
</tbody>
</table>

Fecal sludges: the material removed from latrine chambers and septic tanks; require treatment methods different than regular wastewater

and wastewater as well as treatment processes for their removal.

We emphasize that nonconventional approaches and technology innovation have important roles in meeting the sanitation needs of unserved communities, as is similarly advocated for in water supply (26). Because of the unique contexts of unserved communities, it is critical that the range of technologies considered for a project be as diverse and broad as possible. Local innovations and traditional approaches as well as technologies applied elsewhere in similar contexts should be surveyed. However, new approaches should not be scaled up until there is sufficient evidence that they are effective. Typically, when newer approaches are implemented, more resources should be invested in an effective monitoring program to ensure that performance is adequate.

The sanitation components in this section are discussed roughly in order of increasing complexity, which often coincides with increasing cost. For example, pit latrines are discussed before flush toilets, and management of the waste (fecal sludges and greywater) where nonflush toilets are used is discussed before that of flush toilets. For wastewater treatment, on-site management is discussed before natural treatment systems, which are followed by mechanical wastewater treatment. A summary schematic of how the various system components fit together is provided in Figure 1 [see also (12, 27)].

Many different factors must be considered when choosing the most appropriate sanitation scheme. For example, specific technical factors, including costs, land and energy requirements, treatment efficiency, and sludge production, are summarized in Table 2 for the most common wastewater treatment processes. It is important to note that some of the technologies presented in this section are not appropriate for many types of unserved communities because of their high costs, energy requirements, and management needs. For example, the energy required for sanitation varies dramatically for different technologies, and energy can represent a major portion of operation costs. Most on-site options require zero energy inputs. Centralized collection and treatment schemes range from having no energy inputs (e.g., gravity flow sewer system followed by waste stabilization ponds) to having substantial energy costs (e.g., pumping and aeration for activated sludge). The average electricity use in the United States is 0.3 kWh/m³ of wastewater, including collection and treatment (28). If the entire world’s wastewater were treated in this way, it would require approximately 90 billion kWh/year, representing 0.6%
1 Calculation based on the following values: 6.6 billion people, 40 g biochemical oxygen demand (BOD)/person/day, 350 mg BOD/liter (21), and 15,746 billion kWh consumed globally in 2005 (29). Of course, only a fraction of the global population currently produces wastewater because most people have simple latrines or no sanitation at all. If the 200 million tons of wastewater currently produced that is untreated were treated using U.S. technology, it would require 63 million kWh/year.

4.1. Toilets

Various toilet options are in widespread use throughout the world. Ventilated improved pit (VIP), composting, and urine-separating dry latrines do not require any water, pour-flush latrines require small amounts (but piped water is not necessary), and flush toilets require a piped water supply. All toilet types can be designed with either a squatting platform or a pedestal seat. When a waterless option is used, separate treatment of household greywater is required (Section 4.3). Handwashing facilities must also be provided; one option for households without running water is the tippy tap (31). There is some evidence that the effectiveness of soap, ash, and soil is similar when used for handwashing (with water) (32, 33). Waterless, alcohol-based hand sanitizer (34) is a new alternative being piloted in Mexico and Tanzania (cost and effectiveness have not yet been determined) (A. Pickering, personal communication; F. Reygadas, personal communication). All toilet options may be constructed as stand-alone units or incorporated into the dwelling. The design and materials used for the superstructure varies widely, depending on local preferences, available materials, and financial resources.
Table 2  Wastewater treatment systems and typical performance<sup>a,b</sup>

<table>
<thead>
<tr>
<th>Treatment scheme&lt;sup&gt;c&lt;/sup&gt;</th>
<th>Removal efficiency</th>
<th>Requirements</th>
<th>Economics</th>
<th>Total HRT (days)</th>
<th>Sludge production (m³/person/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BOD (%)</td>
<td>N (%)</td>
<td>P (%)</td>
<td>Fecal coliform (%)</td>
<td>Land (m²/person)</td>
</tr>
<tr>
<td>Septic tank</td>
<td>35–40</td>
<td>&lt;30</td>
<td>&lt;35</td>
<td>&lt;90</td>
<td>0.01–0.05</td>
</tr>
<tr>
<td>Primary treatment</td>
<td>30–35</td>
<td>&lt;30</td>
<td>&lt;35</td>
<td>&lt;90</td>
<td>0.02–0.04</td>
</tr>
<tr>
<td>Advanced primary treatment</td>
<td>45–80</td>
<td>&lt;30</td>
<td>75–90</td>
<td>&lt;90</td>
<td>0.04–0.06</td>
</tr>
<tr>
<td>Natural treatment systems</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anaerobic pond</td>
<td>&gt;60</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Facultative pond</td>
<td>75–85</td>
<td>&lt;60</td>
<td>&lt;35</td>
<td>90–99</td>
<td>2–4</td>
</tr>
<tr>
<td>Anaerobic pond + facultative pond</td>
<td>75–85</td>
<td>&lt;60</td>
<td>&lt;35</td>
<td>90–99</td>
<td>1.5–3.5</td>
</tr>
<tr>
<td>Anaerobic pond + facultative pond + maturation pond</td>
<td>80–85</td>
<td>30–65</td>
<td>&gt;50</td>
<td>99.9–99.9999</td>
<td>3.0–5.0</td>
</tr>
<tr>
<td>Constructed wetlands</td>
<td>80–90</td>
<td>&lt;60</td>
<td>&lt;35</td>
<td>99.9–99.9999</td>
<td>3.0–5.0</td>
</tr>
<tr>
<td>Anaerobic systems</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UASB</td>
<td>60–75</td>
<td>&lt;60</td>
<td>&lt;35</td>
<td>90–99</td>
<td>0.03–0.1</td>
</tr>
<tr>
<td>UASB + maturation pond</td>
<td>77–87</td>
<td>50–65</td>
<td>&gt;50</td>
<td>99.9–99.9999</td>
<td>1.5–2.5</td>
</tr>
<tr>
<td>Trickling filter systems</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low-rate trickling filter</td>
<td>85–93</td>
<td>&lt;60</td>
<td>&lt;35</td>
<td>90–99</td>
<td>0.15–0.1</td>
</tr>
<tr>
<td>High-rate trickling filter</td>
<td>80–90</td>
<td>&lt;60</td>
<td>&lt;35</td>
<td>90–99</td>
<td>0.12–0.25</td>
</tr>
<tr>
<td>Activated sludge (AS) systems</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conventional (continuous flow) AS</td>
<td>85–93</td>
<td>&lt;60</td>
<td>&lt;35</td>
<td>90–99</td>
<td>0.12–0.25</td>
</tr>
<tr>
<td>Extended aeration (low rate) continuous flow AS</td>
<td>90–97</td>
<td>&lt;60</td>
<td>&lt;35</td>
<td>90–99</td>
<td>0.12–0.25</td>
</tr>
<tr>
<td>Sequencing batch reactor (intermittent flow)</td>
<td>90–97</td>
<td>&lt;60</td>
<td>&lt;35</td>
<td>90–99</td>
<td>0.12–0.25</td>
</tr>
<tr>
<td>Activated sludge with biological N&amp;P removal</td>
<td>85–93</td>
<td>&gt;75</td>
<td>75–88</td>
<td>99–99</td>
<td>0.12–0.25</td>
</tr>
<tr>
<td>Oxidation ditch</td>
<td>&gt;95</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> Adapted from von Sperling (22).

<sup>b</sup>The values provided are useful for comparison purposes, but may vary widely from location to location (especially cost). Note that values are for warm climate regions; land area is greater in colder climates.

<sup>c</sup>Abbreviations: BOD, biochemical oxygen demand; HRT, hydraulic retention time; N, nitrogen; O&M, operation and maintenance; P, phosphorus; UASB, upflow anaerobic sludge blanket; yr, year.
4.1.1. Ventilated improved pit latrine. The VIP latrine is a chamber excavated from the soil, covered by a platform with two holes: one for excreta and one for a ventilation pipe (25, 37). The ventilation pipe is dark colored with a screen covering the top and extends from the chamber to a height of several meters to vent odors and trap insects. Collected fecal material undergoes slow decomposition, but pits eventually fill up (within 5 to 10 years, depending on size and use). Options for removal and treatment of the fecal sludge are discussed in Section 4.2. The pit is permeable so that liquids (urine) can leach into the soil. However, the liquids contain high nutrient concentrations and pathogens. To prevent contamination of other water resources, the pit should typically be at least 30 m from any water source (e.g., well or stream), and the bottom should be at least 1 m above the groundwater table. Because soil types vary greatly, however, the amount of treatment that occurs in the soil before the waste reaches nearby surface and groundwater may allow closer separation for some conditions, whereas for others there may be insufficient treatment of waste [e.g., see (38)].

4.1.2. Aboveground and urine-separating latrines. In many regions, the groundwater table is too high, at least during the rainy season, for VIP or pour-flush chambers to be used. In this case, aboveground storage of the fecal waste is needed [disposal of washwater from anal cleansing can still be integrated (39, 40)]. Most of the designs for this type of latrine also incorporate nutrient recovery from the waste and are thus termed ecological sanitation, or ecosan. The potential to recover nutrients from human waste may make ecosan preferable, even in areas where other sanitation options are feasible.

Aboveground latrines are typically designed with two chambers; while one chamber is in use, the other chamber stores and treats previously deposited material. It is also common to separate the urine and feces, which allows for a smaller storage chamber, improved treatment of the fecal waste, a reduction in odors and flies, and decreased likelihood of pathogens seeping into groundwater (41, 42). For nutrient recovery, it makes particular sense to separate the urine, as it contains far fewer pathogens than feces and about 90% of the nitrogen and 60% of the phosphorus (43, 44). At the household level, the urine can be collected and used directly as fertilizer, whereas the feces is treated for 6 months or longer in the storage chamber by addition of wood ash or quicklime to raise the pH and absorb moisture, which helps to inactivate pathogens (40). For large-scale systems, other treatment and reuse options are possible (40, 45). Although it is commonly suggested to use the stored feces as fertilizer, it is very likely that infectious pathogens are still present (46, 47); burying the waste under the soil surface to prevent human contact may be a safer practice.

4.1.3. Pour-flush latrine. A pour-flush latrine combines features of a pit latrine and a conventional flush toilet (25). Urine and feces are deposited into a shallow chamber, and a small volume of water (2–3 liters) is manually added to flush the wastes into a drain pipe with a water seal to prevent odors from entering the superstructure. Similar to a VIP latrine, solids collect in the pit (see Section 4.2 for removal and treatment options), whereas liquids leach into the soil. The additional liquid presents greater potential for groundwater contamination. An alternative to on-site disposal of the waste is to connect the drain pipe to a sewer (Section 4.5). Pour-flush latrines are particularly appropriate when water is used for anal cleansing.

4.1.4. Flush toilets. Flush toilets provide mechanical flushing of wastes using water from a storage chamber. This blackwater, either separately or combined with greywater, must always be collected and treated prior to reuse or disposal either on-site (Section 4.4) or in a centralized system (Sections 4.5, 4.6, 4.7). Modern low-flush toilets use 6 liters or less of water, whereas older designs use 20 liters or more per flush. Other designs for water conservation include: dual-flush toilets, a handwashing station that drains into the toilet storage tank, and
waterless urinals. Urine separation can also be incorporated into flush toilets (45).

4.2. Management of Fecal Sludges

Whereas composting and urine-separating latrines incorporate reuse and disposal of urine and feces into their design, the collection chambers of VIP and unsewered pour-flush latrines will eventually fill up, and either a new one must be constructed, or the fecal sludges must be removed. In rural areas, it is often easiest to build a new pit. Alternatively, if animal husbandry is practiced (e.g., cows, pigs), the animal and human waste can be collected and treated together. The anaerobic digestion of animal waste, resulting in the production of biogas (mostly methane), is widely practiced in some regions of the world, with over 5 million household biodigesters in China and India alone (48). Many designs exist, including concrete or brick pits, as well as tubes constructed from sheets of plastic (48). The biogas produced is typically used for household cooking and lighting, and it is associated with improved health if it offsets or replaces indoor burning of biomass. Codigestion of human wastes can occur in the same digestion chamber. Eventually, the solids will need to be removed from the digester and may still contain pathogens, in particular helminth eggs. Thus, these wastes should be reused or disposed of in a manner that protects human health (49).

In urban areas with constrained space, latrine pits must be emptied. The removal and treatment of fecal sludges represents a major challenge to the safe and sustainable use of latrines in urban areas. Manual removal of fecal sludges is widely practiced out of necessity, but it is recognized as unsafe for the workers and is only partially effective because the pits may be too deep to empty completely. Vacuum pump trucks (such as those used for emptying portable toilets and septic tanks) can be used for emptying wet pit latrines (e.g., located below the water table); however, they are expensive and often too large to navigate the narrow streets in dense urban settlements. Innovative pumping technologies that are smaller, can be pushed manually, and can pump thick fecal sludges are being used in several cities, and these offer income-generating opportunities for small-scale entrepreneurs [e.g., the Vacutug (50–52)].

Fecal sludges, despite having undergone some degree of treatment in the pit, may contain infectious pathogens and must be handled and disposed of or reused in a manner that protects human health (50). Further treatment is necessary, unless the volume is small and land is available for burial. One option is to transfer the material to a wastewater treatment facility via the sewerage network or vehicle transport. However, fecal sludges are highly concentrated, so conventional wastewater treatment processes may not be effective. Treatment options for fecal sludges are still under development and include ponds and drying beds (high ammonia concentrations may inhibit algal and plant growth), co-composting with other wastes, and anaerobic digestion (53, 54). There is an urgent need for additional research on low-cost, effective methods for collection and treatment of fecal sludges.

4.3. Greywater Collection, Treatment, and Disposal/Reuse

Separate collection, treatment, and disposal or reuse of greywater is required if nonwaterborne sanitation is used, but it may be desirable for any household to facilitate local reuse. Greywater consists of all the residual water generated by a household (e.g., discard water from food preparation, bathing, laundry), except toilet waste (blackwater). Greywater represents a risk to both humans and the environment due to the presence of fecal pathogens (e.g., from bathing and laundering of contaminated clothes, especially diapers) as well as detergents, oil/grease, and sediments (55).

If there is no demand for greywater reuse, the simplest disposal option is an on-site soakaway pit (25). Prior to reuse, or discharge to a local water body or an open drainage, treatment is required; a wide range of options are
available, ranging from filtration to biological treatment (55, 56). The most attractive option for reusing greywater is irrigation, for which the World Health Organization (WHO) has published guidelines (49), but there are many other options as well (Section 4.8).

4.4. On-Site Collection and Treatment of Wastewater

When flush toilets are used, on-site collection and treatment of the wastewater (combined toilet flush water and greywater) is required if population densities are too low to make centralized collection of wastewater economical. Where centralized collection is technically possible, on-site treatment may still be lower cost and have other advantages such as enabling water reuse at the household level, or preventing discharge of treated effluent to sensitive water bodies.

4.4.1. Septic tank and leach field. Most on-site treatment operates by gravity flow and does not require energy inputs. A typical system consists of a settling chamber (e.g., septic tank) from which the liquid supernatant is discharged to a leach field. A typical leach field consists of perforated pipes that distribute the water at the base of a gravel-lined ditch (24, 25). The degree of treatment provided by the soil is highly dependent on local factors (e.g., soil type, temperature, and distance to groundwater), and poorly designed systems can cause significant groundwater contamination. Dramatic improvements in the performance of on-site systems can be achieved through the use of fiberglass septic tanks (which do not leak); effluent vault screens to retain solids; and pressurized, shallow trench, distribution systems (24). The necessary components are not widely available, however, and the need for a pump may make such upgrades infeasible.

4.4.2. Options for further on-site treatment. Additional treatment of wastewater at the household level may be desirable, either to enable reuse of treated effluent or because the soil conditions in the leach field do not provide adequate treatment. A wide range of technologies is available (57, 58). For example, an intermittent sand filter can be used, which mimics soil treatment. Pressurized wastewater is distributed at the top in intermittent doses, and a biofilm on the unsaturated sand provides treatment as the water trickles through (24). Another option, which has received significant attention recently, is constructed wetlands (Section 4.6.2). Other options mimic larger-scale processes, but many are very expensive, and few have undergone rigorous, long-term testing (58).

4.5. Centralized Collection of Wastewater

Sewers are pipe networks that collect and transport wastewater from individual households to a discharge point, in most cases a wastewater treatment plant (Sections 4.6 and 4.7).

4.5.1. Conventional sewerage. Conventional sewerage uses fairly large-diameter pipes that are buried beneath roadways (59). Strong materials are used to withstand the load from traffic above. Flow is not pressurized (typically pipes are less than one-third full), and a minimum slope is required to maintain sufficient velocities to mobilize solids. Depending on the topography, pipes must be installed at great depths, and pump stations are required to lift wastewater to shallower depths. Complex manholes to allow access for maintenance are required at regular intervals. Conventional sewerage requires regularly laid-out city blocks with streets that are improved (paved or compacted soil) and wide enough for vehicle access to service sewer lines (60).

4.5.2. Low-cost sewerage. Two main classes of sewerage have been developed that are significantly lower-cost than conventional sewerage; savings are typically ~30%, but can be greater than 50% (60–62). Both employ smaller-diameter pipes that are laid at shallower
4.5.2.1 Simplified sewerage. Simplified sewerage is similar to conventional sewerage, except that less conservative standards are used for the design (25). Condominial sewerage is a specific type of simplified sewerage in which the sewer pipes are laid under yards or sidewalks rather than under streets; this approach can decrease the length of pipes necessary, further decreasing costs.

4.5.2.2 Settled sewerage. In settled sewerage, wastewater from one or more households is settled in a tank prior to discharge to the sewer (25). Because the sewers do not receive solids, they can be designed to flow at lower velocities. Settled sewerage is an obvious choice for centralized collection of wastewater in communities that already have septic tanks but that can no longer dispose of wastewater on-site.

4.5.3. Pressurized and vacuum sewerage. Pressurized and vacuum sewers are used in industrialized countries to reduce costs for lower-density settlements (24). Both types can be installed at shallower depths, and pressurized sewers follow the grade of the land surface; thus, they are also attractive where either the gradient or the subsurface (e.g., rock) makes conventional gravity flow sewerage cost prohibitive. For pressurized sewerage, pretreatment is required at the household level (septic tank or grinder pump). A pressurized system requires pumps at the individual households, whereas a single vacuum pump can serve an entire community.

4.6. Natural Treatment Systems

Natural treatment systems (NTSs) rely on ecological processes to treat wastewater. Their main advantages over mechanical systems (Section 4.7) are lower cost, lower energy inputs (typically zero), and less O&M (fewer mechanical systems), and they can potentially provide habitat and aesthetic value (64). Natural systems are largely controlled by environmental variables (e.g., temperature, sunlight, wind); thus, their performance is variable, although they can operate effectively in most climates. NTSs are commonly used in industrialized countries to treat the wastewater from small- and medium-sized communities (typically <100,000 inhabitants). In developing countries, an NTS will often be preferable to mechanical treatment. NTSs are particularly well suited to preparing wastewater for reuse in irrigation (Section 4.8.1).

4.6.1. Waste stabilization ponds. Waste stabilization ponds (WSPs) are the most widely used NTS and can provide complete treatment of wastewater, although pretreatment to remove sand and grit is still necessary (65). A typical WSP system consists of a series of constructed ponds, ranging from 0.5 to several meters in depth. Passive inlet and outlet structures can be used, and flow can be entirely by gravity. The initial pond can be anaerobic or facultative (aerobic layer overlying anaerobic layer), and the final maturation pond(s) should be aerobic. The total detention times are long, ranging from weeks to months. As a result, sedimentation is much more efficient than in a mechanical treatment plant. Bacteria consume soluble organic matter and then settle to the bottom of the pond. Algae provide oxygen via photosynthesis to aerobic bacteria, in contrast to mechanical treatment plants that use pumps to provide oxygen. Nutrients are removed to some extent by a range of processes. Pathogens in all four classes (see Table 1) are removed efficiently both by settling and inactivation (in maturation ponds), which is primarily due to sunlight-mediated processes. As a result, subsequent disinfection is not usually needed.

Effluent from a well-operating WSP can be directly used for irrigation or aquaculture (Section 4.8.1). In most cases, WSP effluent can also be discharged directly to surface waters, as the algae do not exert an immediate oxygen demand (21). To protect sensitive water bodies from eutrophication, however,
additional removal of algae and nutrients (e.g., by rock filter or wetland) may be required.

There are several key factors that must be considered in the design of an effective WSP system. Sludge production is much lower than in mechanical systems (Table 2); nonetheless, sludge will eventually need to be removed. Because sludge removal, treatment, and disposal are costly compared to the other O&M activities, it must be planned in advance. The hydraulic design of WSP is also important, and improved guidelines have recently been developed to avoid flow patterns that decrease performance (65). Advanced, integrated pond systems (AIPSs) can be used to more closely control and improve treatment performance over conventional WSPs (65). AIPSs are more expensive, have greater O&M requirements, and also require electricity; they should only be considered when it is clear that benefits will outweigh added costs and where resources exist to support them.

4.6.2. Constructed wetlands. Constructed wetlands (CWs) are most commonly used for secondary or tertiary treatment and are preceded by a septic tank, anaerobic reactor, WSP, or mechanical treatment plant. CWs have shallower depths than WSPs (~0.5 m), are planted with emergent vegetation, and also have algae in open water areas. They may have surface or subsurface flow (no standing water), and the flow direction may be horizontal or vertical (subsurface only) (64, 66, 67). The vegetation can be based on native plants and serves several important functions, including supporting growth of microorganisms on plant roots, stems, and litter; uptake of wastewater constituents; interception and filtration of particulate matter; and modification of system hydraulics. CWs require more land area than WSPs (21) but are particularly well suited for “polishing,” such as removing particles, nitrate, pathogens, and heavy metals. They provide better aesthetics and habitat than WSPs.

4.6.3. Soil-based treatment. The application of wastewater to land combines treatment (as the water filters through the soil) and disposal, and it is one of the oldest forms of wastewater management (24). Slow rate processes are similar to irrigation and are most attractive when integrated with crop production (Section 4.8.1). Alternatively, rapid infiltration basins can be used to increase the infiltration rate (decreasing the required land area).

4.7. Mechanical Wastewater Treatment

Mechanical wastewater treatment plants can be designed to treat the flow from small communities or megacities. Compared to a NTS, they produce more consistent effluent quality and require less land area; these benefits are a result of using more energy (e.g., for pumps, aeration, and other moving parts) to provide faster and more controlled treatment. In addition, most mechanical treatment has substantial requirements for operation (e.g., adjusting mechanical equipment, supplying input chemicals, sludge disposal) and maintenance (upkeep and replacement of mechanical equipment), which can make them poor choices for many unserved communities. This type of treatment system should only be built when it is clear that institutional capacity and financial resources exist to provide the ongoing services to run the plant.

In contrast to an NTS, mechanical wastewater treatment is divided into discrete unit processes and may include one or all of the following:

1. Pretreatment removes sand and grit by settling, and large objects by screening.
2. Primary treatment removes particles by sedimentation.
3. Secondary treatment removes dissolved organic matter biologically through its consumption by bacteria. Secondary treatment may also include some degree of biological nutrient removal.
4. Tertiary treatment removes additional constituents, ranging from small particles to nutrients and other trace chemical compounds, and includes a wide range of unit processes. Tertiary treatment may
be required to prepare water for certain types of reuse.
5. Disinfection inactivates pathogenic organisms.
6. Sludge treatment stabilizes and disinfects the solids that are produced during primary and secondary treatment.

Options for primary and secondary treatment and disinfection are reviewed in this section. A comparison of typical performance and cost of mechanical treatment options and natural treatment systems is provided in Table 2.

4.7.1. Primary treatment. Primary treatment involves removal of particles via settling.

4.7.1.1 Sedimentation. Primary sedimentation occurs in large rectangular or circular tanks. The amount of time the water spends in the reactor is typically 1–2 h. As the water moves by laminar flow (minimal mixing), the settleable solids accumulate at the bottom of the tank. These solids are scraped into a drain and are pumped to the sludge processing portion of the plant. Tube or plate settlers can be combined with chemical treatment (see below) to provide high-rate settling (23).

4.7.1.2 Advanced primary treatment. The efficiency of primary sedimentation can be increased by the addition of a chemical coagulant prior to settling, and this is called advanced primary treatment (APT) or chemically enhanced primary treatment (CEPT) (23, 68). The coagulant decreases the net negative surface charge on the wastewater particles, increasing the probability that they will stick together to form larger particles, which are removed more efficiently. Chemical coagulants include iron [e.g., Fe(Cl)₃] and aluminum salts [e.g., Al(SO₄)₃]. Natural coagulants, such as the extract from Moringa oleifera seeds, have also been used and may be a promising local alternative (69).

4.7.2. Secondary (biological) treatment. The net result of all types of secondary treatment is the conversion of dissolved biochemical oxygen demand (BOD) (Table 1) and nutrients into bacterial cells, which are removed by either settling or a membrane. By retaining or returning a portion of the bacteria to the reactor, high densities of bacteria are maintained to provide rapid treatment of the wastewater. One anaerobic and three aerobic processes are described below, listed roughly in order of increasing complexity. Anaerobic treatment [e.g., upflow anaerobic sludge blanket (UASB)] has several potential advantages; it does not require aeration, and the methane produced by anaerobic bacteria can be captured, resulting in net energy production and lower operation costs. In addition, less sludge is produced because anaerobic bacteria have slower growth rates than aerobic bacteria. For aerobic treatment, oxidation ditches and trickling filters are common for smaller facilities. UASBs and oxidation ditches can treat raw wastewater (no primary treatment required), and the sludge produced is well stabilized and may not require further treatment. For more in depth comparisons between these processes, along with other configurations, see (22, tables 4.7–4.21; 23, tables 8.15–8.17; 70, section 7.7).

4.7.2.1 Upflow anaerobic sludge blanket. UASB reactors are the most common anaerobic treatment process after ponds and have experienced high rates of adoption in some developing countries. Wastewater enters at the bottom of the reactor and flows upward through a “blanket” of bacteria. Despite the upward flow, the reactors operate by gravity, and no pumping is necessarily required. The BOD removal is slightly lower than for aerobic processes, so additional treatment may be necessary (22).

4.7.2.2 Trickling filters. Trickling filters are towers filled with packing material; historically rocks were used, but lightweight plastic materials are now widely available, cheaper, and have greater surface area. A large surface area is important to support the growth of a biofilm for BOD removal. Primary wastewater is distributed at the top of the tower by sprayers, and the water trickles over the biofilm. Mats of
biofilm periodically slough off and are removed in secondary clarifiers.

### 4.7.2.3 Activated sludge

Activated sludge has many different configurations and is the most widely applied process for secondary treatment. In its most common form, activated sludge consists of a large aerated tank with suspended bacteria. The bacteria are subsequently removed in secondary clarifiers, and a fraction is returned to the aeration tank. The main operating cost is for aeration and mixing; either air or pure oxygen (generated on-site) may be used. The activated sludge process has been studied in phenominal detail, and mechanistic models are available to predict performance [e.g., (71)]. Molecular tools are also being applied to understand the complex microbial ecology that exists in these selective reactors [e.g., (72)]. Oxidation ditches are often a lower-cost option for activated sludge treatment for small communities. They are oval-shaped reactors in which the water circulates horizontally; aeration and mixing are provided by surface aerators, which require less energy than the bubble diffusers used for many activated sludge configurations. A secondary sedimentation basin (clarifier) is usually required to settle bacteria, but additional sludge treatment may not be necessary. Sequencing batch reactors (SBR) combine biological treatment and secondary sedimentation into a single reactor by treating one batch of wastewater at a time and by alternating between aerated and settling periods.

### 4.7.2.4 Membrane bioreactors

Membrane bioreactors (MBRs) are a recent development, and only a few full-scale systems have been constructed. The effluent is withdrawn through a membrane that is typically submerged in the aeration tank, so that both biological treatment and removal of bacteria are accomplished in one reactor. Depending on the pore size of the membrane, very small particles, and even some dissolved constituents, can be removed, producing a higher-quality effluent compared to other secondary processes. However, more information is needed on sludge production and characteristics, as well as the energy requirements of MBR processes (73).

### 4.7.3. Nutrient removal

If wastewater is discharged to surface or groundwater, additional nutrient removal is usually required beyond that achieved during typical primary and secondary treatment to prevent ammonia toxicity, eutrophication, and pollution of drinking water supplies (see Table 1 for typical removals). Nutrient removal adds significantly to the cost and complexity of a treatment plant. Reuse of treated wastewater for irrigation (Section 4.8) can be a more cost-effective solution, since nutrients are left in the wastewater for the benefit of crops.

#### 4.7.3.1 Nitrogen

Urea is the main nitrogen source in wastewater and is quickly converted to ammonia. Ammonia removal is a two-step process: (a) Nitrification, an aerobic process, converts ammonia to nitrate, and (b) denitrification, an anaerobic process, converts nitrate to nitrogen gas. Typical secondary treatment achieves some nitrification, and the process is enhanced by increasing the length of aerobic treatment. Nitrate, however, causes methemoglobinemia (blue baby syndrome) in infants, and its removal may be required if the wastewater discharges to a drinking water source. Both ammonia and nitrate can cause eutrophication, so nitrification is usually insufficient for discharge to freshwater bodies. Secondary treatment can be further modified to provide anoxic zones for denitrification (22, 23).

#### 4.7.3.2 Phosphorus

Phosphorus is typically present in wastewater as phosphate, which also causes eutrophication. Secondary treatment can be modified to facilitate enhanced biological phosphorus removal. However, the process is often not stable enough to provide consistently low phosphate levels, and chemical precipitation of phosphorus may be required (22, 23).

### 4.7.4. Pathogen removal and inactivation

Pathogens can be either physically removed...
from wastewater or inactivated. Physical remo-
val processes include primary and secondary
sedimentation (Sections 4.7.1 and 4.7.2) as well
as tertiary treatment processes such as filtra-
tion (Section 4.8.2). Physical removal results in
concentrating the pathogens in a residual waste
stream (sludge, in the case of sedimentation),
which must be further treated to inactivate the
pathogens. Disinfection results in inactivating
the pathogens, so that they can no longer cause
infection, although they may still be physically
present in the wastewater.

There are four classes of human pathogens
in wastewater (Table 1) (75–77). Because of dif-
ferences in size, life cycle, and structure, these
organisms vary greatly in their susceptibility
to different removal and inactivation processes.
Also, pathogens themselves are rarely measured
in wastewater, because the methods are difficult
and expensive, there are too many different or-
ganisms, and they are not always present. In-
stead, indicator organisms are measured, such
as fecal coliform bacteria, a class of bacteria that
is part of the normal intestinal flora of warm-
blooded animals.

The most common disinfectants used in
wastewater treatment are reviewed below
(23). Chlorine is the most common disinfect-
ant worldwide and is effective against many
pathogenic bacteria and viruses, but chlorine
is ineffective against protozoan cysts, such as
Cryptosporidium oocysts. If treatment of cysts
is necessary, physical removal should be used
prior to disinfection (Section 4.8), and/or a
more effective disinfectant (e.g., ozone or UV
light) should be used. UV light is becoming
common because it does not produce known
disinfection by-products and can inactivate
Cryptosporidium oocysts. Ozone has not been
widely used for wastewater disinfection.

4.7.4.1 Chlorination. Chlorine is a strong ox-
idant and inactivates pathogenic organisms by
cause damage to biomolecules either on the
surface or inside of the organism. The efficacy
of chlorine depends on the pH of the wastewa-
ter, the concentration of other substances in
the water that react with chlorine, and the degree
to which pathogens are embedded in particles.
These factors determine the necessary dose,
which may vary substantially over time and for
different wastewaters. Chlorine is most com-
monly applied as a liquid (sodium hypochlo-
rite, NaOCl), or for small systems as a solid
(calcium hypochlorite, Ca(OCl)₂); chlorine gas
is becoming less common owing to safety con-
cerns. The reaction of chlorine with organic
matter can lead to the formation of disinfection
by-products, some of which are known
carcinogens. The human health risk posed by
such compounds is believed to be far smaller
than the risk posed by the pathogenic organi-
sms and should not be a concern for wastewater
disinfection. If wastewater disinfected with
chlorine is to be discharged to the environment,
it may be necessary to remove the residual chlo-
rine by addition of a reduced sulfur compound
(e.g., sulfur dioxide) to prevent negative im-
pacts on aquatic organisms. A recent innovation
similar to chlorine is the on-site production of
mixed oxidants, which include chlorine along
with other more reactive species that may be
more effective against Cryptosporidium (78).

4.7.4.2 Ozone. Ozone is a much stronger
chemical oxidant than chlorine. Ozone is an un-
stable gas (O₃(g)) and must be produced on-site,
then transferred to the water. Ozone should not
be used if significant bromide is present in the
wastewater (typical if influenced by seawater)
because of the formation of brominated disin-
fection by-products.

4.7.4.3 Ultraviolet light. Short wavelength
(254 nm) UV light can cause direct damage to
DNA and RNA of organisms such that they
cannot reproduce. UV lamps are typically sub-
merged in a reactor through which the wa-
ter flows; the necessary exposure time depends
upon the concentration of other compounds
in the water that absorb UV light and reduce
its intensity as it passes through the water. UV
is also not effective at penetrating particles,
which can protect pathogens that are hidden in-
side. Therefore, UV is only effective after the
The majority of suspended solids and dissolved BOD have been removed.

### 4.7.5. Sludge treatment and beneficial use.

Sludge is composed of settled solids from the wastewater (primary treatment) as well as bacterial cells that grow during secondary treatment. Using conventional technologies, sludge is typically generated at a rate of 1 dry ton/10,000 person equivalents (79). Adequately and safely handling this volume can require significant operational and financial resources; thus, sludge production must be considered when choosing treatment processes (Table 2). Untreated sludge contains pathogens and possibly chemical contaminants and is suitable only for disposal in a landfill. Sludge treatment reduces the pathogen content and the volume of sludge, which can reduce the costs associated with transportation. Both energy and nutrients can be recovered from sludge during treatment, which can greatly improve the economics and sustainability of sludge handling (80). Treated sludge is commonly called biosolids. Some of the main treatment and reuse options are discussed below (22, 23). Prior to treatment, sludge thickening is usually required; following treatment, the sludge is usually dewatered before transport.

#### 4.7.5.1 Sludge treatment options.

- **Sludge drying beds** are the lowest-cost option for small applications, but they can only be used during the dry season. Sludge is distributed in a thin layer over an underdrain, typically sand, and dries by draining and dehydration. Solar heating can enhance pathogen inactivation. Anaerobic digestion of sludge is the most common treatment method, resulting in production of biogas (mostly methane), which can be used directly as a fuel or to produce electricity. Sufficient quantities of methane can be produced to potentially supply all of the energy requirements of the treatment plant. If methane is not used as a fuel source, it should be flared on-site because methane has a greenhouse gas forcing 22 times greater than carbon dioxide. Alkaline treatment involves adding quicklime to sludge, which raises the pH and temperature and absorbs water. Alkaline treatment is typically lower cost than other treatment options, but quicklime has a significant environmental footprint, and the mass of sludge produced is higher (80). Composting of sludge is typically performed in combination with other organic wastes, such as plant trimmings and municipal solid waste. Incineration of sludge can be used to achieve a much larger reduction in volume. Even when coupled with energy production, however, sludge incineration requires a net input of energy to dry the sludge. The capital costs can also be prohibitive.

#### 4.7.5.2 Beneficial use.

Land application to agricultural fields, pasture, or forests is the most common beneficial use of biosolids. Biosolids are preferable to industrial fertilizers because they contain organic carbon (improves soil texture), the nutrients (e.g., N, P, K) are released slowly (better for crops, and also less likely to run off and pollute surface or groundwaters), and they contain micronutrients. Application restrictions are based on the level of treatment the biosolids received to minimize the risk of human contact with remaining pathogens. Heavy metals and other chemical contaminants must also be carefully monitored so that acceptable application rates are not exceeded. If there is no demand for use of biosolids in agriculture, or if contaminant levels are too high, they may be incorporated into cement or brick manufacturing, which can have significant economic and environmental benefits (80).

### 4.8. Water Reuse

Treated wastewater is a valuable resource, and reuse rather than disposal can increase the benefits of wastewater collection and treatment. A main benefit of reuse is avoiding the degradation of surface waters (by not discharging wastewater), as the cost of removing nutrients to adequate levels to prevent eutrophication can be very high. Other benefits may include reducing the costs of wastewater treatment, recovery of nutrients, reducing demand on existing water...
supplies, groundwater recharge, and provision of a constant and reliable source of water for users (23, 73, 81).

4.8.1. Types of reuse and water quality standards. Use of wastewater for irrigation is by far the most common type of reuse. Wastewater provides a constant supply of irrigation water to farmers and also contains nutrients to fertilize the crops. Unfortunately, the use of untreated wastewater is a widespread practice, which represents a significant health risk to farmers, their families, and consumers of the crops (82). The WHO guidelines can be used to develop safe regulations for reuse in agriculture, which include both water quality guidelines as well as other protective measures (81). Simple treatment processes, such as WSP, can be used to achieve the WHO guidelines, making reuse an affordable and safe practice.

Other types of reuse include landscape irrigation, aquaculture, industrial uses (e.g., cooling water, process water), toilet flushing, and groundwater recharge. Water quality standards for these uses vary around the globe, and some of these uses may require advanced treatment, as described in the following sections (73).

4.8.2. Advanced (tertiary) treatment processes. The processes described below are commonly used to prepare wastewater for reuse applications that have stringent water quality requirements. For example, because of severe water scarcity, Windhoek, Namibia, has been successfully treating its wastewater using a series of advanced treatment processes and blending it into the drinking water supply since 1968 (73).

4.8.2.1 Tertiary filtration. Tertiary filtration most commonly involves granular media, such as sand, but recently, textiles and other media have been shown to be effective (73). Rapid sand filtration requires significant amounts of energy to backwash the filters, whereas slow sand filtration requires less energy, but greater land area. The goal of filtration is to remove particles, including pathogens such as protozoan cysts. Filtration is also considered a preparation step for more effective disinfection (chlorine, UV, or ozone).

4.8.2.2 Membrane filtration. Depending on the properties of the membrane, ranging from microfiltration to reverse osmosis, very small particles to dissolved constituents can be removed from wastewater (73). As higher levels of treatment are achieved (removal of smaller molecules), more energy is required to force water through the membrane under pressure. Thus, membranes require significant energy to operate. In addition, all membrane processes produce a waste stream in which all of the removed compounds are concentrated; disposal of this rejected water can be a major challenge.

4.8.2.3 Advanced oxidation processes. Advanced oxidation processes can be used to remove organic chemicals from water that are resistant to other forms of treatment (e.g., pharmaceuticals, pesticides, disinfection by-products), including those that may pass through a reverse osmosis membrane (73). The processes all generate the highly reactive hydroxyl radical, which can oxidize most compounds.

5. COSTS

Estimates of the costs of comprehensive sanitation are presented below. The capital and O&M costs of individual treatment technologies were presented in Table 2; however, those costs do not include the entire system costs (for example, toilet and sewerage). The allocation of these costs is complicated by the public and private good characteristics of improved sanitation, an issue that is discussed in more detail in Section 7. Quantifying the many potential benefits of sanitation is a matter of substantial debate, and will not be reviewed here [e.g., see (82a, 82b)].

5.1. Estimates of Sanitation Costs

There is a wide range in the costs associated with improved sanitation depending on technology choices and water usage. The U.S. federal government has invested more than
$80 billion in the construction of public sewage treatment plants and related facilities since the passage of the Clean Water Act in 1972 (83). It is estimated that an additional $390 billion will be required over the next two decades to replace dated infrastructure and to build new treatment plants (83). Using the World Bank’s suggested investment rate in water and wastewater infrastructure of 1.5% of gross national product (GNP), it would take many developing countries centuries to pay for the infrastructure to provide their entire population with sanitation services that include flush toilet, sewerage, and wastewater treatment to meet EU effluent standards (84). For example, with their current population and GNP, India would require 746 years, and Kenya would need 1034 years (84). Thus, the economic appropriateness of different sanitation technologies deserves due consideration in the decision-making process.

Significant cost savings can be accrued with the choice of low-cost and effective sanitation technologies. For example, Whittington (85) estimates a cost of $18 per household per year for low-cost sanitation technologies at a consumption level of 50 liters per person per day (e.g., condominial sewer and WSP), versus $180 per household per year for conventional technologies at a consumption level of 200 liters per person per day (e.g., conventional sewer, primary sedimentation, and activated sludge) (85). These estimates include the capital and O&M costs over the infrastructure’s lifetime. Actual costs, however, may vary dramatically between countries and between rural and urban settlements owing to differences in the costs of labor, materials, and sewerage. Other researchers have estimated the full capital outlay with one year of O&M for different sanitation technologies. Connection to a sewer with secondary wastewater treatment (e.g., activated sludge) would cost $450/person versus $150/person for an indoor dry single-vault urine-diverting toilet with decentralized piped greywater treatment using NTS (9). The Stockholm Environment Institute estimates that the capital costs with one year of O&M for comprehensive ecological sanitation, including dry urine-diverting toilets and greywater treatment, would be between $25 and $330 per person in periurban and urban areas and between $3 and $8 per person in rural areas (86). Urban sanitation is more expensive because of the added costs of decentralized greywater treatment as well as transportation of waste for composting or agricultural application (9).

5.2. Global Investments in Sanitation

Numerous estimates of the necessary annual investment to achieve the MDG for sanitation have been published. The range is significant owing to methodological and definitional differences (10, 86). Annual investments of $11 billion to $20 billion between 2000 and 2015 represent the lower and upper bounds for providing access to low-cost improved sanitation (87). The most recent WHO publication estimates a necessary annual investment in new infrastructure of $14.2 billion between 2005 and 2014 (10). Providing municipal wastewater treatment adds $70 billion per year to the estimates (87). Alternatively, providing the entire MDG target population with ecosanitation is estimated to require $15 billion per year between 2003 and 2015 (9). Even the highest published estimates are likely too low, as they do not account for the costs of policy planning, monitoring, regulation, and financing (86). In addition to the initial investment, the continued annual investment required for O&M is estimated at about 10% of capital costs, which amounts to more than $20 billion per year for existing infrastructure in developing countries plus that built between 2005 and 2015 to meet the sanitation MDG (10).

The World Health Organization and United Nations Children’s Fund Joint Monitoring Program (JMP) estimates that governments and aid agencies invested only $3.1 billion per year in sanitation throughout the 1990s (10). Although investments in water and sanitation are expected to increase, funding is still projected to lag behind what is necessary to meet the MDG (88). In addition to monetary
shortfalls, Official Development Assistance (ODA) flows tend to be heavily biased toward large-scale infrastructure projects, which often lack sufficient planning for long-term O&M and seldom serve those who lack basic access to sanitation facilities (88, 89). In 2002, only 12% of the total ODA to the water and sanitation sector went to countries where less than 60% of the population has access to an improved water source (88, 90).

6. PRIVATE-SECTOR PARTICIPATION

Private-sector participation in water and sewerage services is a contentious subject on both moral and practical grounds (91, 92). Advocates view private-sector involvement as a means of increasing investment and improving the efficiency of water and sewerage services. Opponents of privatization argue that it threatens to further marginalize poor communities. Potential users in multiple countries consistently voice resistance to privatization of water and sanitation services (93, 94). However, these social preferences, as well as environmental considerations, are conspicuously absent from most debates about private participation (95). Academic case studies of privatization show contradictory results with respect to access by the poor, quality and efficiency of service, and job creation; economic studies are inconclusive as to whether the private sector has improved coverage and/or access by the poor (96). In light of a very active debate about the role that the private sector should play, the reality is that private investment and/or management in water and sewerage services is quite significant for basic, household-level facilities (97), but it is very limited for centralized wastewater services, accounting for service to approximately 5% of the world’s population (91). Most investment in sewerage and wastewater treatment comes from the public sector, international development assistance, and user fees (91). There are various mechanisms for private engagement in the wastewater sector, and they are differentiated by their allocations of risk, responsibility, and ownership in the private entity. Concession contracts are most common, followed by build-operate-transfer-type contracts (98).

Between 1991 and 2006, 371 out of 526 privately financed water and wastewater treatment projects involved a sewerage collection and/or wastewater treatment component (98). Since 1999, the rate of private investment in new projects has slowed, as the most attractive, large-scale investments have already been pursued (91, 98, 99). The geographic distribution of private-sector involvement reflects the sector’s selective investment: 90% of the total investments are in East Asia/Pacific and Latin America/Caribbean regions, the low- and middle-income regions with the largest economies and most rapidly urbanizing populations (91, 98). In contrast, only 0.2% of the total private-sector investments are in sub-Saharan Africa in spite of the fact that 64% of the region’s population does not have access to improved sanitation (98, 100). Between 1991 and 2006, 11% of private-sector water and sanitation projects (equivalent to 38% of investment) were cancelled or on the verge of termination (98).

The limited role of the private sector in sewerage and wastewater services suggests that privatization alone will not bring about the rapid expansion in wastewater treatment coverage that many international development agencies were hopeful for a decade ago (92, 95). It has been argued that the success of private partnerships in water and sanitation projects is contingent upon the local government’s ability to oversee and regulate the private operator (92). Some of the factors cited as leading to efficient and equitable privatization are a strong regulatory capacity that might include contracts regarding the quality and extent of services, requirements of provision to the poor, a ceiling on user fees, and the ability to attract competition (92, 101, 102).

In contrast to large-scale private investors, small-scale independent providers (SSIPs) have emerged to meet unmet demands for sanitation infrastructure and related services in primarily low-income settlements and often at the
household level (97). In Jakarta, for example, individually financed septic tanks are serviced by a competitive local industry (103). Sludge extraction from pit latrines has also become a competitive industry for small entrepreneurs in many cities, making the service more affordable and accessible to households and communities (104). Most SSIPs are unregulated, and there is debate as to whether they should remain so. There are concerns that regulation could eliminate the flexibility in how SSIPs charge for service, increase transaction costs, and require a quality of service that makes the costs of business prohibitive, thus leaving the poor without service (104, 105).

7. CHOOSING TECHNOLOGIES FOR THE LOCAL CONTEXT

The technical, financial, social, and institutional challenges associated with implementing successful sanitation schemes largely stem from the complex distribution of benefits that emerge from sanitation. At the household level, improved sanitation provides a safe, dignified, and hygienic place for defecation, whereas at the community level and beyond, complete sanitation can improve public health, environmental protection, water resources management, economic growth, and achievement of development targets (12).

Frameworks for choosing appropriate sanitation technologies have been developed that attempt to overcome the limitations of common planning approaches that often result in systems that fail technically, socially, and financially. The frameworks incorporate early consultation with key stakeholders, consideration of their differing priorities and their knowledge and resource capacity to implement and manage the system, and options for reuse and resource recovery (12, 27, 106). Because it is unlikely that any system of technologies can meet all objectives, it is critical that technology choices emerge from an iterative planning process that provides an opportunity to reach compromises among competing objectives. Financial and institutional realities as well as barriers, such as unattainable design or performance standards, will also be revealed through a holistic planning process (12).

The planning process is markedly different for existing households versus construction of new buildings. For existing households, the present infrastructure (e.g., latrine versus flush toilet, community versus household water supply, sewer network, roads) will favor certain technical options, as will the availability of space. Construction of new housing is an opportunity to implement innovative sanitation approaches that are locally tailored from the start of the planning process.

Current financing patterns, including the allocation and availability of money, present an enormous barrier to spreading access to improved sanitation. Although there is certainly a need to increase overall investment in the sector, poor allocation of existing funds, inflexible payment regimes, and inadequate planning for future O&M costs are recognized economic challenges (12, 62, 88, 107, 108). Low effective demand for sanitation among poor communities has long been acknowledged; however, there is still debate as to the cause. One hypothesis is that poor communities are not presented with a sanitation option that is both affordable and desirable. Recent evidence suggests that in some circumstances latent demand can be stimulated with improved access to credit such as microloans (unpublished field report by J. Davis, R. Hall, A. Pickering, S. Vedala & G. White, Improving access to water supply and sanitation for the urban poor: the role of microfinance, Stanford University). Another explanation for the lack of demand is that the societal benefits of sanitation, such as reduced burden of disease and environmental damage, are mistakenly employed to motivate private demand. Rather, understanding and leveraging a household’s or individual’s private desires, such as improved status, and increased comfort and convenience, can be a more effective means of generating a long-term and sustainable demand for sanitation (97). The public benefits of sanitation justify intelligent subsidies that can act as catalysts for demand promotion and for
viable, self-sustaining sanitation schemes (97). International development agencies once promoted a policy of full cost recovery for water services; however, consensus among organizations, including the Asian Development Bank and the Organisation for Economic Co-operation and Development, is shifting to reflect an understanding that subsidies are critical for reaching the poor (62).

In most countries, numerous ministries, including the Ministries of Water, Health, Rural Development, and the local government all have responsibility for some aspect of sanitation (97). This fragmented delegation of roles leaves the sector devoid of an advocating body that can ensure sanitation receives sufficient priority and resources (11, 62, 104). Thus, institutional reform that appoints accountability for all aspects of sanitation provision to a central agency is sorely needed among all demographics of the unserved.

The sections below address the unique opportunities and challenges associated with four demographics: planned and unplanned high-density urban settlements, small/periurban settlements, and rural settlements. Although not all households fit into one of these categories, they cover the majority of unserved populations.

7.1. Unplanned High-Density Urban Settlements

As of 2007, for the first time in history, the majority of people in the world were living in urban areas (4). Today, in most large urban areas in the developing world, between 25% and 50% of the population lacks sanitation service that is sufficient to significantly reduce the risk of waterborne disease; this statistic is even worse in small cities (4). The JMP estimates that to achieve the MDG one billion urban dwellers must gain improved sanitation between 2002 and 2015 (100). Geographically, the greatest urban need exists in East Asia, followed by Southern Asia, sub-Saharan Africa, and Latin America and the Caribbean (9).

Slum dwellers make up 43% of the urban population in developing regions, and they account for the majority of those without access to basic sanitation (e.g., a latrine) in urban areas (12). These individuals often have a low ability to pay for services and lack officially sanctioned or legal tenancy, making the provision of sanitation a particularly formidable challenge technically, economically, and institutionally.

7.1.1. Technical challenges and opportunities. Unplanned, high-density urban areas face technical and financial constraints that narrow the array of potential sanitation and wastewater treatment options. Adaptability is also an important characteristic to suit the transient nature of many unplanned settlements. Nonwaterborne latrines will often be the most appropriate option because they are low cost and do not require a piped water supply to the household or a sewer network. Adequate planning for the removal, transport, and treatment of fecal sludge when the latrines become full is critical to the success of on-site sanitation. Where waterborne toilets are used (most likely pour-flush), low-cost sewerage can substantially decrease costs compared to conventional sewerage. Technology options for wastewater treatment should be considered after opportunities to reuse treated water have been identified to allow the type of treatment to be matched with the water quality requirements of the reuse option (27). A decentralized approach using several smaller treatment facilities located closer to the point of reuse, rather than one large facility, may be preferable to reduce transport costs (70).

In slums where entire homes can be less than 10 m², private toilets may be logistically infeasible (12). Where space and/or finances are constrained, shared sanitation facilities, if adequately maintained and acceptable to residents, are one option. International agencies, including United Nations Children’s Fund (UNICEF) and WHO, are reluctant to consider shared toilet facilities because they often fail due to inadequate maintenance (12). However, studies of these failures identify a number of specific causes, largely related to a lack of clear ownership and accountability over the facilities (12). A number of innovative solutions
have emerged to better allocate responsibility for O&M, improving the success rate of these facilities (104, 110, 111). Although work remains to eliminate maintenance challenges associated with shared facilities, and to ensure their desirability, successes in Africa, India, and elsewhere suggest that the option should not be eliminated a priori.

7.1.2. Finance challenges and opportunities. Chronic underinvestment because of unwillingness to finance services for the urban poor, as well as legal restrictions on investments in unplanned areas, has hindered the expansion of sanitation services (11, 91, 111). In response, community-based federations in more than 20 nations have emerged to improve infrastructure inadequacies, including toilets and low-cost sewerage (89). A UN task force concluded that the efforts of these federations are the most operationally and economically effective means of improving local livelihoods in slum communities to date (89). Over the past decade, community federations have reached tens of millions of slum dwellers and have demonstrated ability to scale up their influence to entire cities as well as nations. The federations work in partnership with local governments and nongovernmental organizations and draw on the financial, human, and material resources within their communities to drive development projects (89). Using external financial assistance to establish revolving funds that can be accessed through microloans by households, federations, or small entrepreneurs for sanitation infrastructure and related services has been shown to foster more sustainable and scalable projects than provision of large (but unpredictable) subsidies (113). For residents with no ability to pay, cross-subsidies or government grants can be used to implement and maintain shared facilities (114). Community federations have not taken responsibility for wastewater treatment, however. This service is expected to be provided by the municipal government.

7.2. Planned, High-Density Urban Settlements

Planned, high-density urban settlements are typically found in the center of a city, other areas zoned for high-density residential or mixed-use buildings, and commercial centers. Buildings range from individual residences to high-rises.

7.2.1. Technical challenges and opportunities. All of the technologies discussed in Section 4 have the potential to be feasible in high-density, planned urban settlements, but the challenge is giving informed consideration to the wide array of choices. Unfortunately, design engineers and local stakeholders are often biased toward choosing conventional technologies because they lack training and knowledge of other alternatives (12, 27, 62, 115).

Nonwaterborne toilets may be considered if there is sufficient space. Even for apartment buildings, urine-separating dry latrines may be
used, with collection of wastes in basement vaults. If waterborne toilets are used, sewerage is usually necessary because land area is not sufficient for on-site disposal. Low-cost sewerage is an option when installation can occur in backyards or under sidewalks, whereas conventional sewerage will be required for installation under roads with heavy traffic. Sewer networks can account for upward of 70% of the cost of conventional wastewater treatment schemes (116); in built-up neighborhoods, excavating roads and disrupting residents adds significantly to the expense of centralized sewerage. Options for wastewater treatment and reuse are similar to those for unplanned settlements and may be integrated.

7.2.2. Finance challenges and opportunities. Planned, high-density urban regions have the most success harnessing funding for sanitation infrastructure through loans and private investment (62). However, cost recovery is notoriously challenging because the typical technologies used are very expensive, e.g., conventional sewerage plus mechanical wastewater treatment (104); there are countless examples of failed sanitation projects caused by financial collapse. Thus, the long-term ability to finance and maintain such infrastructure must be ensured. A well-functioning low-cost system is far superior to a defunct high-cost scheme that does not provide public health and environmental benefits.

In planned urban areas where the population has a range of abilities to pay for sanitation, creative payment mechanisms, such as microfinance, taxes, government grants, cross-subsidies, and “lifeline” rates, can be used to make a sewer connection accessible to different customers (91, 92; unpublished field report by J. Davis, R. Hall, A. Pickering, S. Vedala & G. White, Improving access to water supply and sanitation for the urban poor: the role of microfinance, Stanford University). Differential service, such as offering household and shared facilities or on- and off-site sanitation options, is another way to make sanitation accessible and affordable to all. Financing schemes that rely least on continuous external funding have proven most sustainable (12).

7.2.3. Institutional challenges and opportunities. Inadequate institutional capacity is often cited as a barrier to more rapid and sustainable implementation of improved sanitation (3, 12). In planned urban areas, the demographic often most attractive to the private sector, strong government oversight is key to ensuring the quality and scope of service. The challenges for many governments are consolidating responsibilities for the sector and formulating clear objectives (104). For public and privatized sanitation, outdated policies and standards often make it unaffordable or technically impossible for service providers to reach the poor and to implement the solutions best suited for users (e.g., sewer design mandates, one-size-fits-all effluent standards).

7.3. Small Urban and Periurban Centers

Small urban centers with medium population densities are an increasingly common demographic, often exhibiting traditional features of both urban and rural areas (115, 118). Of the global urban population, 53% lived in urban centers with less than 500,000 people as of 2000, and the UN projects that most urban population growth through 2015 will occur in small urban areas (119). The expansion of sanitation services has thus far failed to keep pace with the rate of growth in these areas: More than one billion people who lack access to adequate sanitation live in small urban centers (62). In comparison to large, high-density urban areas, there are unique challenges and opportunities for providing sanitation services in small and periurban centers.

7.3.1. Technical challenges and opportunities. All of the technologies discussed in Section 4 are potentially viable in periurban and small settlements. Where plot sizes are large enough, on-site options for treatment and disposal can be considered. When waterborne
toilets are used, housing density is the main factor influencing whether on-site or low-cost sewerage is more cost-effective. Of course, the technology choice for treatment will also greatly impact the cost. Because periurban and small urban centers are more likely to be in close proximity to agriculture, reuse of wastewater for irrigation may be particularly attractive. Lower land costs will make natural treatment systems more cost-effective than they are for larger cities.

7.3.2. Finance challenges and opportunities. Large-scale private investors have demonstrated less interest in small and periurban centers compared to large urban centers because it is harder to leverage economies of scale, and there tends to be a smaller population with the ability to pay the full costs of service (62). At the same time, small cities tend to have weaker local governments and fewer financial resources of their own. It has been shown that offering access to credit through microloans can stimulate latent demand and lead to more rapid spread of sanitation in these regions (11). SSIPs also play an important role in small urban areas by offering locally tailored solutions and by keeping costs down through competition (11). More research is necessary to understand the best ways to involve SSIPs in formal efforts to expand access to sanitation, including the most appropriate levels of regulation and oversight.

7.3.3. Institutional challenges and opportunities. In small and periurban centers with significant fiscal constraints, governments often see sanitation as having fewer returns on investment than other infrastructure projects (62). Revealing the hidden costs of inadequate sanitation (e.g., environmental degradation, economic losses, threatened water security) and growing demand among users and decision makers is an important step in closing the sanitation gap in these regions. Another consequence of governments’ limited financial resources is an inability to employ experts locally with the technical capacity to design sanitation schemes or evaluate the appropriateness of suggestions from consultants (62). Decision making that is not informed by experts with an understanding of the local context risks outcomes that are unsustainable or that do not meet the intended objectives of users and governments.

Where governments prioritize sanitation, there are numerous institutional characteristics of small urban settlements that may facilitate the implementation of sanitation services, including better intergovernmental collaboration, more informal accountability, more acceptance of partnerships with local organizations, and less conflict between the citizens and state (62). Although these traits may be more likely to occur in small rather than large urban areas, they are by no means universal; lack of coordination between land-use planning, human settlement patterns, and water and sanitation services have been identified as key drivers of residents seeking informal access to services in periurban regions (95).

7.4. Rural Settlements

Rural settlements are on the decline in most parts of the world; in 1970, two thirds of the world’s population still lived in rural areas, and by 2007, it was less than half (4). However, the JMP estimates that just under 900 million rural residents must gain improved sanitation between 2002 and 2015 in order to achieve the MDG (100). Geographically, the need in rural regions is concentrated in Central Asia and Eurasia, the only two regions in the world where the need for rural access outstrips that of urban access (9). The majority of unserved rural areas are quite remote, which exacerbates the challenge of sustainable service provision (100).

7.4.1. Technical opportunities and challenges. One of the key drivers for promoting improved sanitation in rural areas is to prevent the contamination of groundwater. In rural regions, where populations are dispersed, on-site collection and treatment is the most viable sanitation option. Where water tables are high, pit latrines and septic tanks
are insufficient to protect groundwater from contamination by fecal pathogens and nitrate. In this situation, urine-separating latrines with aboveground storage are the best option, which also enable households to capture nutrients. For households with animals such as pigs or cows, codigestion of human and animal waste to produce methane is an attractive option.

Inadequate maintenance is a major cause of rural sanitation project failure (11). Because rural households often lack access to trained technicians, it is critical that households are adequately trained in the O&M of sanitation technologies and that replacement parts—if relevant—are locally available. Sanitation projects must also encourage appropriate O&M by proving a superior alternative to the defecation and disposal options that prospective users are practicing. Open defecation, particularly during rainy or monsoon seasons, poses an enormous public health risk by spreading pathogens to surface waters or edible crops. Community-level and environmental health, however, seldom provide enough incentive for household-level investment in sanitation (114).

7.4.2. Finance challenges and opportunities.
Effective demand for improved sanitation is notoriously limited in rural areas; consequently, these regions are less targeted for subsidies or other aid than high-density urban areas (11). Social marketing, focusing on status, convenience, cleanliness, and the potential for biogas heat and electricity, can play an important role in mobilizing internal and external financial resources for sanitation (11, 114). The importance of community participation through in-kind labor, and the role that it should play in water and sanitation projects for the poor, is controversial (107, 120). However, volunteer labor can be an important and effective means of reducing the costs of implementing improved sanitation (11). Like other demographics, improving access to credit for households with some ability to pay, as well as to independent service providers or community-based organizations, appears promising based on experiences in sub-Saharan Africa (121). Providing targeted subsidies to the poor is also shown to be an effective financial mechanism for spreading rural sanitation (122, 123).

7.4.3. Institutional challenges and opportunities.
Dispersed rural settlements tend to have the weakest institutional support for planning and implementing sanitation (11). Community-based projects ensure the role of households in decision making; however, they still require technical support, supply-chain support, and other assistance that centralized agencies provide (11). Significant improvements in rural access to sanitation will depend upon the emergence or restructuring of government institutions to take responsibility for securing and allocating funds and other resources for rural sanitation.

8. CONCLUSIONS
This chapter has sought to provide an understanding of the sanitation challenge that is grounded in an awareness of the technology options, as well as the economic and sociopolitical challenges and opportunities. The unserved population without complete sanitation services is not only enormous (more than 2.6 billion), but also extremely heterogeneous. A wide range of proven sanitation technologies are available to meet the diverse needs of the unserved. Many of these technologies are appropriate for poor communities (e.g., latrines, WSP), and many are innovations that have emerged specifically to minimize the costs of effective sanitation (e.g., pour-flush latrines, low-cost sewerage, UASB). However, planning and design processes for sanitation infrastructure often do not incorporate adequate consideration of lesser-known technologies; political and institutional barriers can also unduly prevent their use. The long-term implications of technology choices (e.g., O&M costs, institutional capacity to manage infrastructure, energy and water use, environmental impacts) are also rarely given adequate consideration, which may result in project failure. Capturing the resource
value of fecal waste and wastewater (water, energy, nutrients) can dramatically improve the cost-effectiveness and acceptability of sanitation projects, and options should be considered at the beginning of the planning process. There is still need for technology innovation in, for example, methods for collection and treatment of fecal sludges. In addition, improved analytical methods and technical capacity are needed for monitoring human waste, wastewater, and sludges to ensure that treatment and disposal or reuse schemes are meeting goals of protecting human and environmental health. A significant increase in investment is needed, along with creative financing mechanisms that target the needs of poor populations.

**SUMMARY POINTS**

1. There are 2.6 billion people who do not have access to improved sanitation. Among those with access, some have very poor service, and less than 15% of the wastewater generated by those with waterborne sanitation is treated.

2. Existing sanitation projects have often failed to meet the main goals of complete sanitation—to protect human health and the environment and to recover resources from waste (e.g., water, nutrients, energy)—because of lack of capacity and resources.

3. On-site sanitation options that eliminate the need for a sewerage network and have low O&M costs appear to be the most promising for rural and unplanned settlements.

4. In settlements where space or preexisting infrastructure prohibits on-site sanitation, condominial sewers are an approach to centralized sewerage that is proven to cost less than conventional sewers.

5. The most cost-effective way to prevent or reverse eutrophication of surface waters is often through reuse of wastewater in agriculture, whereby nutrients are applied to crops, offsetting the application of synthetic fertilizer and avoiding costly nutrient removal via advanced wastewater treatment.

6. Appropriate water quality standards are essential to guide the design of sanitation infrastructure that will protect public and environmental health. Ongoing monitoring is also critical to ensure compliance with effluent standards and to inform operational decisions.

**FUTURE ISSUES**

1. More rigorous research is needed on innovative sanitation technologies as well as on applications of existing technologies to meet the specific needs of unserved communities (e.g., household treatment of feces from on-site systems that are sufficient to eliminate pathogens and enable safe reuse; centralized management of fecal sludges, including removal, transport, treatment, and reuse; performance of treatment processes under different climatic conditions and for wastewater with different characteristics).

2. Better quantitative analysis of the long-term costs and benefits of different sanitation approaches is needed (including indirect health and environmental impacts) to enable informed decision making about technology choices.

3. Effective measures must be identified and implemented for closing the knowledge gap between design engineers and local stakeholders regarding awareness and appropriate selection of the wide array of sanitation options.
4. Enhanced institutional capacity and policy reform to eliminate barriers to adoption of lower-cost sanitation technologies (e.g., removal and treatment of fecal sludges, condominial sewerage, natural treatment systems) must occur before universal sanitation can be a reality.

5. Sanitation is substantially underfunded, and there is need for better understanding of how to equitably and sustainably allocate the economic burden among stakeholders, particularly the poor.

6. Successful cases of shared sanitation facilities in poor settlements have emerged; however, the long-term sustainability of these projects must be monitored, and further research on effective maintenance regimes is required.

7. Local capacity development for establishing appropriate water quality standards and monitoring programs is needed.

8. More detailed data are needed on current access to sanitation, including types of service, how much wastewater is treated, etc.

DISCLOSURE STATEMENT

The authors are not aware of any biases that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

We thank the reviewers from this journal for their thoughtful comments and suggestions. We also thank Duncan Mara and Marcos von Sperling for their comments on an earlier draft. Support from the National Science Foundation award to K.N. (BES-0239144) and a Chang Lin Tien Scholarship in Environmental Sciences and Biodiversity to A.M. are gratefully acknowledged.

LITERATURE CITED


35. Deleted in proof

36. Deleted in proof


63. Deleted in proof

64. Crites RW, Middlebrooks EJ, Reed SC. 2005. *Natural Wastewater Treatment Systems.* Boca Raton, FL: Taylor & Francis


93. Rakodi C. 2000. “Getting the pipe laid is one matter and getting the water flowing through the pipe is another”: user views on public-sector urban water provision in Zimbabwe, Sri Lanka, Ghana, and India. *Int. Plann. Stud.* 5:365–91
109. Deleted in proof
112. Deleted in proof
117. Deleted in proof

Nelson • Murray


**RELATED RESOURCES**


Contents

Preface .................................................................................................................. v
Who Should Read This Series? ................................................................................ vi

I. Earth’s Life Support Systems

Climate Modeling
Leo J. Donner and William G. Large ................................................................. 1

Global Carbon Emissions in the Coming Decades: The Case of China
Mark D. Levine and Nathaniel T. Aden ............................................................ 19

Restoration Ecology: Interventionist Approaches for Restoring and
Maintaining Ecosystem Function in the Face of Rapid
Environmental Change
Richard J. Hobbs and Viki A. Cramer .............................................................. 39

II. Human Use of Environment and Resources

Advanced Passenger Transport Technologies
Daniel Sperling and Deborah Gordon .............................................................. 63

Droughts
Giorgos Kallis .................................................................................................. 85

Sanitation for Unserved Populations: Technologies, Implementation
Challenges, and Opportunities
Kara L. Nelson and Ashley Murray ................................................................. 119

Forage Fish: From Ecosystems to Markets
Jacqueline Alder, Brooke Campbell, Vasiliki Karpouzi, Kristin Kaschner,
and Daniel Pauly .............................................................................................. 153

Urban Environments: Issues on the Peri-Urban Fringe
David Simon ....................................................................................................... 167

Certification Schemes and the Impacts on Forests and Forestry
Graeme Auld, Lars H. Gulbrandsen, and Constance L. McDermott .................. 187
III. Management, Guidance, and Governance of Resources and Environment

Decentralization of Natural Resource Governance Regimes  
Anne M. Larson and Fernanda Soto .................................................. 213

Enabling Sustainable Production-Consumption Systems  
Louis Lebel and Sylvia Lorek ................................................................. 241

Global Environmental Governance: Taking Stock, Moving Forward  
Frank Biermann and Philipp Pattberg .................................................. 277

Land-Change Science and Political Ecology: Similarities, Differences, and Implications for Sustainability Science  
B.L. Turner II and Paul Robbins ....................................................... 295

Environmental Cost-Benefit Analysis  
Giles Atkinson and Susana Mourato .................................................. 317

A New Look at Global Forest Histories of Land Clearing  
Michael Williams ........................................................................ 345

Terrestrial Vegetation in the Coupled Human-Earth System: Contributions of Remote Sensing  
Ruth DeFries .................................................................................. 369

A Rough Guide to Environmental Art  
John E. Thornes ............................................................................. 391

The New Corporate Social Responsibility  
Graeme Auld, Steven Bernstein, and Benjamin Cashore ...................... 413

IV. Integrative Themes

Environmental Issues in Russia  
Laura A. Henry and Vladimir Doubnovikoff ........................................ 437

The Environmental Reach of Asia  
James N. Galloway, Frank J. Dentener, Elina Marmer, Zucong Cai, Yash P. Abrol, V.K. Dadhwal, and A. Vel Murugan ............................................. 461

Indexes

Cumulative Index of Contributing Authors, Volumes 24–33 .................. 483
Cumulative Index of Chapter Titles, Volumes 24–33 ............................ 487

Errata

An online log of corrections to Annual Review of Environment and Resources articles may be found at http://environ.annualreviews.org