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Review

Decentralized systems for potable water and the potential of membrane technology

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ABSTRACT

Decentralized drinking-water systems are an important element in the process of reaching the Millennium Development Goals, as centralized systems are often deficient or non-existent in developing and transition countries (DC and TC). Most water-quality problems are due to hygiene factors and pathogens. A range of decentralized systems is available to counter these problems, including thermal and/or UV methods, physical removal and chemical treatment.

This review focuses on decentralized systems that treat the potable water (drinking and cooking) of a single household (point-of-use systems) or a community (small-scale systems). For application in DC and TC, important boundary conditions for decentralized systems include low costs, ease of use, sustainability, low maintenance and independence of utilities (energy sources). Although some low-cost systems are available, their application is limited by time-consuming daily operation and maintenance. Other systems are too expensive for the poor populations of DC and TC and in most cases do not fulfill the system requirements described above. Point-of-use systems based on membranes are commercially available and are designed to operate on tap pressure or gravity.

Membrane systems are attractive since they provide an absolute barrier for pathogens and remove turbidity, thus increasing the palatability of the water. The costs of membrane have decreased rapidly during the last decades and therefore membrane systems have also become within reach for application in low-cost applications in DC and TC. Some membrane systems rely on gravity as a driving force, thereby avoiding the use of pumps and electricity. On the basis of the present literature data, no small-scale systems could be identified which meet all the requirements for successful implementation. Furthermore, in the available literature the performance of highly fouling water types has not been reported. For such cases, more extensive studies are required and a need for suitable pre-treatment was identified.

It can be concluded that there are good prospects for decentralized systems based on membranes, but that a need exists for research and development of systems with low costs and low maintenance, specifically designed for DC and TC.

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Contents

1. Introduction

Global assessments by the WHO and UNICEF show that a large proportion of the world's population does not have access to adequate or microbiologically safe sources of water for drinking and other essential purposes: at the beginning of 2000, one-sixth of the world's population (1.1 billion people) were without access to adequate water supplies (Mara, 2003). Insufficient water supplies, sanitation, and hygiene contribute to 3.7% of globally quantified DALYs (indicator for the overall burden of disease) (WHO, 2002). Target 10, described in the Seventh Millennium Development Goal (MDG), states that by 2015 the proportion of people without sustainable access to safe drinking water and sanitation should be halved compared to 1990 (UN, 2006). Considerable progress has been achieved in reaching these goals. According to the most recent sources, the percentage of people using drinking water from adequate sources increased from 71% in 1990 to 80% in 2004 (UN, 2006; WHO, 2004a). However, a large effort is still necessary to reach this goal by 2015. For example, the growing populations of Asia and Africa pose a major challenge, and there are wide disparities among countries and between rural and urban areas. It is foreseen that sub-Saharan Africa in particular will be unable to meet these goals by the year 2015 (WHO, 2004a). Moreover, even if this goal is reached by then, some 11–15% of the world's population will still remain without access to safe drinking water, and solutions are also needed as soon as possible for this large group of people. Evidently, most problems occur in developing countries (''DC'') as well as in the transition and rapidly industrializing countries (summarized by the abbreviation ''TC''). This overview focuses on the problems occurring in DC and TC. The problems in developed/industrialized countries (''IC'') are not addressed explicitly unless related to the situation in DC/TC.

Problems with drinking water in developing and transition countries often concern microbial pollutants, although organic and inorganic chemical pollutants can also play a role (Ashbolt, 2004). Infectious diarrhea is claimed to be responsible for most of the 1.7 million deaths per year (3.1% of all annual deaths) caused by poor water quality, sanitation and hygiene, and 9 of 10 of these deaths are children, virtually all in developing countries. Furthermore, 3.7% of the annual health burden worldwide (54.2 million disability adjusted life years (DALY)) is attributed to unsafe water, sanitation and hygiene (Ashbolt, 2004).

Abbreviations

DC	developing countries
TC	transition countries
IC	industrialized countries/developed countries
POE	point-of-entry
POU	point-of-use
SS	small scale
SSS	small-scale systems
MF	microfiltration
UF	ultrafiltration
NF	nanofiltration
RO	reverse osmosis
ED	electro dialysis
BSF	biosand filtration
DALY	disability adjusted life years

In urban and densely populated areas, the principle of ''economy of scale'' generally favors central solutions for the supply, distribution and treatment of water. However, many existing cases and examples show that such solutions often fail to achieve the desired results in DC and TC, mostly due to political or socio-economic factors (Zerah, 2000; Kyessi, 2005; Gadgil, 1998; Basu and Main, 2001). The outcome is an unreliable water service in terms of quantity and/or quality. It is clear that improving the water quality in an existing water supply system (including the raw water supply, water treatment plant and water distribution network) may be prohibitively costly and time-consuming, whereas only 2.5–5% of tap water is used for domestic consumption (drinking and cooking). Proposed solutions consequently revolve around setting up alternatives such as a separate dual-water supply system or ensuring point-of use treatment for drinking water. Nevertheless, in only a few cases has a dual water supply been officially recognized by the local authorities, notably in China (Daquing, China (Ma et al., 1998)) and in Odessa, Ukraine (Strikalenko et al., 1999). In many cases, the user reaction to the unreliable quality of water is widespread and heterogeneous installation of decentralized point-of-use treatment solutions, especially by the richer part of the population.

In rural areas of DC and TC, centralized drinking water treatment is in general prohibitively expensive, leading to the frequent use of untreated natural water sources (rivers, lakes, groundwater or rain). These sources are generally not well protected and may contain chemical or microbial pollutants, mostly derived from a lack of adequate sanitation and thus contaminated by human and animal excreta which are either active cases or carriers of disease (Gadgil, 1998). In rural or informal urban or peri-urban communities of DC, where a centralized water supply is lacking, decentralized systems are consequently often the only means to improve the quality of water obtained from contaminated sources.

When the necessary investments for the installation and operation of centralized or even small-scale water treatment plants are unavailable to the local authorities or community, it remains up to the households to find their own solutions for water treatment or else bear the health consequences. Moreover, the economic viability of centralized systems is crucial in the sparsely populated rural areas of all countries (including industrialized countries), and a trend towards decentralized drinking water systems can also be observed in these cases.

The use of membrane systems has increased significantly, especially for water and wastewater treatment (Anon, 2006). While membrane sales were US$ 900 million in 1997 (Anon, 1999), the global market in cross-flow membrane systems for water and wastewater applications is expected to grow from US$ 6.7 billion in 2006 to US$ 10 billion in 2010 (Anon, 2006). Most large-scale applications of membrane technology are naturally found in the IC, but a large increase is expected in strongly growing economies like China (Anon, 2006). In principle, membrane technology is also attractive for the TC and DC because it provides absolute barriers for controlling hygiene hazards and its modular construction allows implementation on all possible scales. Although this technology has become more efficient and the costs of membranes have decreased significantly (Churchhouse, 2000), it remains unaffordable for the poorest part of the world population. Research and development of membrane systems aimed specifically for the DC remains limited to isolated cases (Wessels, 2000; Pillay and Buckley, 2003; Goldie et al., 2004; Modise and Krieg, 2004) and is often not published in the available literature (Pillay, 2006).

In the present review, an overview of available POU systems is given and the potential for applying membrane-based POU systems is assessed. Moreover, the relevant research and development needs are identified in order to make the benefits of this technology available to a larger part of the world population. The focus of this review is on disinfection (removal of pathogens), because microbial contamination remains one of the major threats to human health in DC and TC.

2. Problems of the water supply situation in developing and transition countries

2.1. *Water quality and health*

The main drinking-water risks in developing countries are associated with microbial pollution. About two dozen infectious diseases are related to water quality (Arnal et al., 2001). Water-borne diseases are spread by the water acting as a passive carrier for the infecting pathogens. These diseases are predominantly due to fecal contamination of the water source and are thus strongly linked to the sanitation conditions. Use of such water for drinking and cooking, as well as contact with it and its ingestion during bathing and washing, or even inhalation of small droplets in the form of aerosols, may result in infection (Gadgil, 1998). These illnesses can be caused by viruses, bacteria, protozoa or larvae (e.g. cholera, typhoid, bacillary dysentery, infectious hepatitis, leptospirosis, giardiasis and gastroenteritis). Other microorganisms present in water are fungi, algae, rotifers and crustaceans (Arnal et al., 2001). This is the most relevant category of water-supply diseases when discussing the issues surrounding drinking-water treatment. Other categories are water-based diseases caused by water supporting an essential part of the life cycle of infecting agents (e.g. aquatic snails and diseases such as schistosomiasis, dracunculosis, bilharziosis, philariosis and oncholersosis, as well as threadworm and other helminths). Water-related diseases are spread by vectors and insects that live in or close to water (e.g. mosquitoes, flies and insects) and include yellow fever, dengue fever, encephalitis, malaria, filariasis, sleeping sickness and onchocerciasis. Finally, washing-water diseases are caused by a lack of adequate quantities of water for the proper maintenance of personal hygiene (e.g. scabies, trachoma (an eye-infection), leprosy, conjunctivitis, salmonellosis, ascariasis, trichuriasis and hookworm) (Ashbolt, 2004). A total of about 1400 species of infectious organisms known to be human pathogens have been recorded (Ashbolt, 2004). The minimum infectious dose for the average healthy adult varies widely for different microorganisms. It ranges from just a few organisms for *Salmonella typhi* (typhoid causing bacteria), to several hundred organisms for *Shigella flexneri* (dysentery-causing bacteria), and to several million cells of *Vibrio cholerae* (cholera-inducing cells). These doses are significantly lower for infants and small children than for the general adult population (Gadgil, 1998).

In DC and in some cases also in TC, water disinfection methods are generally not applied and cannot guarantee effectiveness even where they are applied. Currently, the most frequently used disinfection method in these countries consists of boiling the water. Given the high energy requirement for boiling and the often limited availability or affordability of energy sources, thermal treatment is frequently omitted. Besides, using wood as an energy source for boiling water results in deforestation (Sobsey, 2002). Consumption of untreated water causes a high rate of infections that, although not severe in most cases, have sometimes been the cause of major epidemics (Arnal et al., 2001). Even if a disinfection agent – mostly chlorine gas or hypochlorite – is used, the presence of suspended matter and colloidal turbidity in the water can protect micro-organisms from effective disinfection and stimulate bacterial growth (Pryor et al., 1998). Coliform organisms are generally accepted by the WHO as indicator organisms for fecal contamination of water and the possible presence of pathogens. Although other bacterial pathogens are less or comparably resistant to disinfection than the coliform organisms, enteroviruses and the cysts of some parasites are more resistant. Therefore, the absence of coliforms from disinfected water does not necessarily indicate the absence of enteroviruses and the cysts of *Cryptosporidium*, *Giardia*, amoebae and other parasites (Gadgil, 1998).

Arsenides and fluoride are among the best-known, widespread and significant naturally occurring waterborne chemical pollutants (Meenakshi and Maheshwari, 2006): guidelines define their maximum acceptable concentrations as 10 μg/l and 1.5 mg/l respectively. In severe problem areas, increased concentrations in drinking water can lead to skin diseases (e.g. hyperkeratosis), cancer (by arsenic poisoning) or crippling diseases (skeletal fluorosis) (Meenakshi and Maheshwari, 2006). These two chemicals alone affect something like a hundred million people in developing countries (Gadgil, 1998). Besides these chemical pollutants, the WHO has set guidelines in the form of tolerable daily intake (TDI) values for the following elements: antimony, barium, boron, cadmium, chromium, copper, lead, manganese, mercury, molybdenum, nickel, selenium and uranium (WHO, 2004b). Guideline TDI values are also set for compounds and ionic groups such as cyanide, nitrate and nitrite. Health risks due to toxic chemical compounds can therefore originate from natural sources (e.g. fluorine, arsenic), industrial sources (e.g. heavy metals), and agricultural sources (e.g. pesticides) (Helmer, 1999). In addition to excessive concentrations, risks may also be due to deficiencies of chemical elements, such as iodine or fluoride (Helmer, 1999). The class of contaminants relating to agricultural sources is often neglected, but is of equally great importance considering that some 3 million people suffer from pesticide poisoning in the developing countries, resulting in a total of 220,000 deaths p.a. (WHO, 1992). Among the organic contaminants, the WHO guidelines address several toxic substances that increasingly find their way into drinking water supplies in developing countries, where agricultural chemicals are commonly used without appropriate regulation and the chemical, dyestuff and process industries are spreading. This list contains chlorinated alkanes, chlorinated ethenes, aromatic hydrocarbons, chlorinated benzenes and 36 pesticides (Gadgil, 1998).

Typically the type of water pollution differs in developing, industrialized and transition countries. WHO statistics confirm that with regard to water quality, microbial contamination of the water supply is the major health risk in developing countries, while in industrialized countries the anthropogenic chemical contamination of drinking water is considered a more significant threat to human health, although the actual risks are low (Helmer, 1999). The urban populations of rapidly industrializing and transition countries of Asia and Eastern Europe are also increasingly facing health risks due to chemical hazards in drinking water. Gadgil states that there is evidence suggesting that the concentrations of anthropogenic chemical pollutants in the drinking water supplies of Eastern Europe and the former Soviet republics are much higher than in the rural areas of most developing countries (Gadgil, 1998). However, the traditional microbial contamination problem in these areas still has not been solved and remains the major threat to human health in some areas (Helmer, 1999; WHO, 2002).

People lacking access to adequate and safe water supplies are most at risk from water-borne diseases. In view of the importance of the water-supply service for health and wellbeing, it is crucial to have reliable knowledge about the status of this service as well as to understand the reasons for the increasing interest in household solutions.

2.2. *The present situation in developing and transition countries*

2.2.1. *Rural communities*

Rural communities are situated further away from the major centers. This often leads to reduced management and supervision capacities for water-supply infrastructures and services (Pryor et al., 1998). Typically, centrally organized infrastructures and services are seldom available, and water is obtained individually from surface or underground water sources. The quality of the surface water is often critical and its quantity may also be limited in arid areas. Where an improved water-supply infrastructure is installed – typically with shared facilities such as bore wells with hand pumps – access is often a limiting factor, as either water availability is critical, the infrastructure has to be shared by many users or the facilities have fallen into disrepair (Lenton and Wright, 2004). Rural communities are generally unable to exploit economies of scale for such community-level water supply solutions. As a result, per-capita improvement costs are generally high, while the potential for cash contributions from households tends to be low. Where water supply infrastructures are already installed, inadequate financial resources for their operation and maintenance, the unavailability of spare parts or technical skills and/or weak institutional arrangements may negatively affect their sustainability (Lenton and Wright, 2004; Swartz, 2000; Momba et al., 2005).

If water treatment technology is used, it is often limited to removing suspended materials by means of media filters with or without coagulation. In such cases, operation and maintenance are essential and loss of filter media or infrequent washing can result in greatly reduced treatment efficiency. Slow sand filtration is also used in some cases, usually at smaller waterworks facilities. Although this achieves some natural disinfection, excessive raw water turbidities during seasons of high rainfall, inadequate operation of the filters with inappropriate flow rates or lack of flow control can result in an inefficient treatment process (Pryor et al., 1998). Besides the technical and financial problems typical of rural communities, there is often also a lack of health-risk perception and related hygiene practice or any information on treatment products (Sobsey, 2002).

2.2.2. *Urban and peri-urban areas*

The concentration of large numbers of people created by rapid urbanization in the second half of the 20th century has produced a potential for distribution efficiencies unavailable to dispersed rural populations. Nevertheless, urban water management has often failed to benefit from this advantage to adequately supply rapidly growing urban populations with water (Basu and Main, 2001). In fact, the dynamics of these rapidly changing situations present a challenge to the provision of water infrastructure and services. Rapid urban population growth – consisting mostly of the poorest households – gives rise to massive shanty towns/slums where the establishment of a centralized infrastructure may be neither economically nor technically feasible (Basu and Main, 2001; Thomas and Ford, 2005).

The estimates of the populations in urban areas with access to a reliable water supply given by the WHO may be set too high (Sobsey, 2002): in some cities, water systems draw unsafe water from unprotected or contaminated sources and deliver it to consumers with no or inadequate treatment, despite being classified as improved and safe. This would imply that the number of people without direct access to safe drinking water may be very much higher than the 1.1 billion mentioned in Section 1.

Another problem contributing to the underestimation of the population served by unsafe water is the contamination of water during its distribution to homes via pipes or carriers. Many cities have protected or improved water supplies and treated water that is microbiologically safe when collected or when it leaves a treatment plant. However, the urban infrastructure for water distribution to consumers is sometimes so inadequate that infiltration of contaminated water can occur due to pressure drops and other intermittent pressure changes, or to deteriorating, open or leaking conveyances, illegal connections and other distribution system deficiencies, which leads to an increased risk of water-borne diseases (Sobsey, 2002). Moreover, in many large cities, including some of the world's megacities, peri-urban settlements are not served by the centralized water system for socio-cultural, economic, political, technological and other reasons. These urban dwellers are forced to make their own informal arrangements (Basu and Main, 2001). For example, in the city of Dhaka, Bangladesh, the number of informal settlements reached 3007 with a total population of 4 million in 1996. The formal system provided only 1643 street hydrants, forcing people to use hand pumps or obtain water from water vendors, unprotected dug-wells, ponds, rivers, canals and swamps (Akbar et al., 2007).

Small towns and former villages that have expanded without their infrastructure systems evolving to a level comparable with large cities are normally excluded from both national water-supply programs targeting rural areas and those focused on cities. They are generally large enough to exploit some economies of scale for the water supply, but are too small and/or dispersed for traditional urban utility management models to operate effectively. These types of communities often have the economic capacity to make considerable improvements in their water supply, but the absence of a supportive institutional framework results in a variety of household-level solutions. As a result, some wealthier households install private wells while other users obtain water from vendors and/or surface water sources (Lenton and Wright, 2004).

2.3. *Problems of the centralized water supply*

The improvement and extension of water treatment remains an important and necessary objective of governments in many countries, and many development agencies assist in this endeavor (Mintz et al., 2001). Centralized water treatment and distribution may be feasible for densely populated settlements of DC given their economies of scale, and already exists in most cities and towns of TC. Where centralized water supplies exist, the renovation of water treatment technologies and distribution networks will improve the water supply situation. However, this demands financial resources and as well as positive changes in water management operation and maintenance. Thus in the case of Targoviste, Romania, it was possible to reduce the cost of a water unit as well as water loss in the network (from 14 million m^3 in 1997 to less than 4.5 million m^3 in 1999) within two years by installing new pressure valves in the pumping system, making minor technical modifications backed up by strong media support and running information campaigns together with the installation of water meters in the apartments of private households (Mocanu, 2000).

In *rural areas* of DC and TC, investments for centralized systems are often unaffordable given the remote locations and lack of financial resources (see also Section 2.2.1). In the rare cases where centralized systems are installed, the system often fails due to unprofessional maintenance and management (Lenton and Wright, 2004). Tap water from a supply network and a central water treatment facility is therefore generally unavailable in rural areas. Typically, water is accessed individually from surface water, groundwater or rainwater, with no source protection or water disinfection before consumption.

A further problem is that the traditional approach to making water/source infrastructure improvements has been influenced by the view that ''contamination of water in the home is relatively unimportant''. ''What matters is whether the water coming out of the tap or pump is contaminated''. However, this view is no longer valid (Moyo et al., 2004): hygiene risks arise not only from the source water – contamination can also take place between source and point-of-use by several mechanisms (Wright et al., 2004; Clasen and Bastable, 2003). Thus recontamination was observed during the storage and handling of clean water due to unhygienic practices in the household in case studies in Zimbabwe (Moyo et al., 2004) and Honduras (Trevett et al., 2005). Contamination can also occur during storage in the household (Brick et al., 2004). In this case, promoting alternative water treatment options such as treatment at the POU is often the most feasible way of improving the water supply situation of the households.

In *urban areas* of developing countries, the inequality of water access and availability, i.e. where services are provided only to the richer part of the population through a central supply and distribution network, is due to political, institutional and economic reasons. Research undertaken by Akbar et al. (2007) shows that the employees of some public water providers prefer not to provide water to informal settlements because this would reduce extra income through bribes. In addition, informal dwellers are continually afraid of eviction, which discourages them from spending money on reliable water supplies (Akbar et al., 2007). International assistance for water supplies through local or national government departments often does not reach the poor either (Akbar et al., 2007). But it is a mistake to believe that the urban poor are unable or unwilling to pay for water. Some studies (Akbar et al., 2007; Daniere and Takahashi, 1999) have shown that most of the poor are already paying higher rates than high-income communities.

It can be concluded from these arguments that approaches relying solely on centralized solutions may work in some regions of DC/TC, whereas in many cases structural problems which are unlikely to be resolved in the foreseeable future lead to malfunctions. Where governments are unable or unwilling to improve the water supply service, the concept of self-help or the involvement of the private sector in local water management often leads to the appearance and introduction of decentralized solutions. Nevertheless, the authorities still maintain the theoretical principle of centralized treatment while neglecting the support in terms of informational, political and economic factors required by decentralized approaches to treatment.

3. Decentralized solutions

Decentralized approaches to supplying water are already applied in many parts of developing and transition countries. These decentralized solutions cover both quality and quantity problems and include the direct use of alternative water sources (ground- or rainwater), household water treatment systems, dual tap water treatment and distribution as well as delivery and sales of treated water. Despite their popularity in some cases, these installations often have an informal character and are rarely accepted or supported by local governments. Regional differences occur in their implementation due to the local socio-cultural, economic and political situation. However, some general situations can be identified in which these technologies are being or may be applied.

3.1. Solutions practiced in cases of limited water quantity

3.1.1. Groundwater wells

When a centralized water supply is not available or the quantity is limited, poor households have to rely on water obtained from rivers or shallow wells. Wells are often the preferred solution, as the distance to them may be shorter, access easier and the water considered to be less polluted. In many cases (Basu and Main, 2001; Palamuleni, 2002; Moyo et al., 2004), households build private shallow wells at their own cost, obtaining water for their family needs or sharing it with neighbors. Wells operated by hand pumps and tube wells with motor pumps are also common. They may be used by local water vendors or the local authorities to provide a community supply (Kyessi, 2005), or by businesses, high-rise apartment blocks, hotels and restaurants in the cities (Basu and Main, 2001). However, there are several constraints on the construction and use of groundwater wells. If hydrogeological data are not available, an efficient planning of groundwater wells is challenging (Charalambous, 1982). Contamination can occur if the wells are placed too close to sources of contamination or if the wells are too shallow. Furthermore, depletion can occur due to overdraft and salinization can occur in case of inadequate drainage (Schmoll et al., 2006; Konikow and Kendy, 2005).

For example, in Yemen the groundwater abstraction in the highland plains exceeds recharge by 400% (Shah et al., 2000). In the Fuyang river basin of North China, the water table of lower aquifers decreased from 8 to 50 m within 30 years, while the industries polluted the upper aquifers (Shah et al., 2000). Besides industrial, agricultural and domestic pollution, groundwater contamination may also be caused by natural occurrence of arsenic and fluoride in some countries (arsenic in Bangladesh, Nepal, Taiwan, etc.; fluoride in Tanzania, South Africa, etc.) (Smedley and Kinniburgh, 2002; Schoeman and Steyn, 2000). If groundwater quality is unsatisfactory, additional treatment is necessary.

3.1.2. Rainwater harvesting

In some semi-arid areas of the world, a knowledge of rainwater harvesting technology has existed and been further developed for centuries. For example, in 50% of the area of Tanzania, people rely completely on rainwater for their survival (Mbilinyi et al., 2005). Rainwater harvesting provides water at the point of use and family members have full control of their own systems, which greatly reduces operation and maintenance problems. There are also examples of community rainwater harvesting systems, when water is collected from roads or fields (Gould and Nissen-Petersen, 1999). The disadvantages of rainwater harvesting are the seasonal variability in supply, the uncertainty of rainfall and often also the unreliable water quality due to infection and regrowth during storage. Harvesting water from roads, fields or even roofs after dry periods may also lead to contamination (Zhu et al., 2004). Other non-conventional modes of access and use of water resources are outside the scope of this review and are described elsewhere (Qadir et al., 2007).

3.2. *Solutions practiced for water quality problems*

3.2.1. *Point-of-use, point-of-entry and small-scale systems*

If a centralized supply exists but distribution or treatment does not function, people have to resort to using groundwater wells or carrying water home from rivers or ponds and/or have to put up with untreated river water or microbiologically contaminated water, and thus an increased risk of water-borne disease. The main pre-condition for the application of decentralized technologies to improve the water quality is active concern by households, community leaders or local NGOs. When the connection between water and disease is understood, the choice of solution depends on local customs, the availability of information and resources as well as the market and the required scale.

Because different definitions for decentralized systems exist, the following definitions are used in the present paper: point-of-use (POU) systems treat only the part of water used for drinking. The minimum requirement for drinking water amounts to about 2 l per person and day, while the maximum for drinking and cooking is 8 l per day (DeZuane, 1997), which implies that the requirement for a four-member family amounts to 8–32 l/day. Point-of-entry (POE) systems refer to the treatment of all the water supplied to a household (Craun and Goodrich, 1999). The treatment capacity is therefore much higher than for POU systems (in the order of 100–150 l per person per day). Small-scale systems (SSS) usually refer to systems of larger scale than POU or POE, but with a distinctly smaller capacity than centralized systems. Typically, SSS treat the water consumed by several families or a small village. The capacity of SSS cannot be unequivocally defined, but usually varies between 1000 and 10,000 l/day. The term ‘‘household systems’’ can refer both to POU and POE systems. The term ‘‘decentralized systems’’ can refer to POU, POE and SSS.

3.2.2. *Available POU technologies*

In principle, all decentralized technologies can be applied in the same way as the centralized treatment of drinking water. For the smallest scale of systems, the POU systems, some specific technologies and systems have been developed, described and evaluated for household use on the basis of several performance criteria. Besides efficiency in improving the microbiological quality of the water and the system costs, these performance criteria include the ease of use of the system or technology, its environmental sustainability, socio-cultural acceptability and potential for dissemination (which also includes availability of skilled personnel able to provide repairs, availability of spare parts, or required maintenance in general). A number of studies and considerable field experience have shown that the introduction of any POU water-treatment technology without consideration of these criteria is unlikely to be either successful or sustainable (Sobsey, 2002). Moreover, systems for decentralized applications should preferably be independent of utilities such as electricity or tap pressure. Some of the POU systems are discussed in the following part of this section on the basis of their performance criteria.

Most of these methods are already being explored or used in DC/TC to some extent (see also Sobsey, 2002).

- Heat and UV-based systems:
  - Boiling with fuel
  - Solar radiation
  - SODIS (combined action of heat and solar UV)
  - UV lamps
- Chemical treatment methods
  - Coagulation, flocculation and precipitation
  - Adsorption
  - Ion exchange
  - Chemical disinfection
- Physical removal processes:
  - Sedimentation or settling
  - Filtration, including membranes, ceramic and fiber filters
  - Granular media filters, including sand filters
  - Aeration

Some of these methods, such as boiling with fuel, are traditionally and widely used, although they may not always be the optimal solution. Other methods (such as SODIS) have a high potential for application. Several of the methods listed are discussed in more detail below.

3.2.2.1. *Heat, UV and chemical disinfection.* *Boiling with fuel* effectively destroys all classes of water-borne pathogens (Sobsey, 1989). However, a major disadvantage of boiling is its consumption of energy in relation to the availability, cost and sustainability of fuel. In areas of the world where wood, other biomass fuels or fossil fuels are in limited supply and must be purchased, the costs of boiling water are prohibitive. Therefore, boiling household water is considered unrealistic and inaccessible to many of the world’s poorest people due to the scarcity and high cost of fuels and the lack of sustainability of biomass or fossil fuels in the community or region (Sobsey, 1989, 2002). Another problem of boiling is that it provides no residual protection: water can easily be recontaminated after cooling and is also associated with the risk of scalding, especially among infants (Mintz et al., 2001).

Solar water disinfection (SODIS) is a simple technology for improving the microbiological quality of drinking water by using solar radiation to destroy pathogenic microorganisms (Mintz et al., 2001).

The SODIS system consists of four basic steps: removing solids from highly turbid (>30 NTU) water by settling or filtration; placing low-turbidity water in clear PET bottles of 1–2 l volume; aerating the water by shaking it in contact with air and exposing the filled, aerated bottles to full sunlight for about 5 h (Mintz et al., 2001; Reed et al., 2000; Wegelin et al., 1994, 2001). The system is suitable for treating small volumes of water (<10 l), especially if it is of relatively low turbidity (<30 NTU).

A potential limitation of SODIS besides its dependence on sunlight for disinfection is that the process is rather laborious. In order to ensure its daily supply, a family of four or more people would need upwards of 17 2-l bottles. In some cases (Murcott, 2005), the drinking-water bottles discouraged people from using the clean water for anything besides drinking directly from the bottles.

Pasteurization without UV can also be carried out using solar energy. If the exterior of the vessel is completely black or similarly capable of absorbing heat (such as most metal containers), only thermal effects occur and temperatures can reach >60 °C. Most enteric viruses, bacteria and parasites are rapidly inactivated at these temperatures (Ciochetti and Metcalf, 1984).

UV irradiation with lamps has received renewed interest in recent years because of its well-documented ability to extensively (>99.9%) inactivate two waterborne, chlorine-resistant protozoans, *Cryptosporidium* parvum oocysts and *Giardia* lamblia cysts, at relatively low doses.

However, UV lamp disinfection has some disadvantages for use as a drinking water disinfectant at household level. Particulates, turbidity and certain dissolved constituents can interfere with or reduce the efficiency of microbial inactivation. A reliable and affordable source of electricity is required to power the UV lamps. These lamps require periodic cleaning, especially in the case of submerged lamps, they have a finite lifespan and must be periodically replaced (Gadgil, 1998). To make the cleaning and replacement possible, an efficient infrastructure is needed, which may not always be possible. This increases the operational costs of UV-based systems and impacts their environmental sustainability.

Chemical treatment is widely used for disinfection purposes. Of the drinking-water disinfectants, free chlorine is the simplest, most widely used and the most affordable. It is highly effective against nearly all water-borne pathogens, with the notable exception of *Cryptosporidium parvum* oocysts and the *Mycobacteria* species (Sobsey, 2002; Mintz et al., 2001; Clasen and Edmondson, 2006). Tablets or powders that combine a coagulant-flocculant and a chemical disinfectant have been described for POU treatment at household level (Rodda et al., 1993; Kfir et al., 1989). Extensive reductions of bacteria, viruses and parasites were reported, and the costs of treatment were estimated to be relatively low (US$ 0.01 /l). However, the socio-cultural acceptance of disinfection with chlorine-containing reagents tended to be low in some cases, due to taste and odor problems (Murcott, 2005). Moreover, if insufficient time intervals are applied for reaction and sedimentation, the effectiveness of these methods is low.

3.2.2.2. *Physical removal processes*. Several types of media can be used, including granular media of various grain sizes. Such mechanical filters may be an attractive option for household treatment because they can be produced on the spot with locally available materials; they are mostly simple, easy to use and potentially long-lived (Wegelin et al., 1991; Galvan and de Victorica, 1997; Lantagne et al., 2007).

However, regular cleaning is required to maintain flow rates at acceptable levels, so that some skills and knowledge are required to operate and maintain these filters, unless they are fully automated (Burch and Thomas, 1998).

Slow sand filtration has been adapted for use in the home and is known as Biosand filtration (BSF). Biosand filters are containers filled with sand in which a bioactive layer is allowed to grow as a means of eliminating disease-causing organisms. Laboratory and field tests showed that BSF removes bacteria consistently if not completely, on average by 81–100%, and protozoa by 99.98–100%. However, these filters have limited virus-removal efficiency (Lantagne et al., 2007; Kaiser et al., 2002).

Furthermore, *paper, fiber or fabric filters* may be applied at household level. They can be effective in the removal of larger water-borne pathogens such as free-swimming larval forms (cercariae) of schistosomes and *Faciola* species, guinea worm larvae within their intermediate crustacean host (*Cyclops*), and bacterial pathogens associated with relatively large copepods and other zooplankton in water, such as the bacterium *Vibrio cholerae* (Sobsey, 2002; Huq et al., 1996). However, these filters are not recommended for the general treatment of household water because their pores are too large to significantly retain viruses, bacteria and smaller protozoan parasites (Sobsey, 2002; Sobsey et al., 2008).

Activated carbon filters, often in the form of pressed blocks, followed by UV disinfection or silver (Ag) pre-coating, are being used as table-top units for additional tap water treatment in TC (Ecosoft, 2007) and IC (Abbaszadegan et al., 1997). However, they have only a limited operating life (six months in the case of Ecosoft) and relatively high costs, making them unaffordable to most of the population in DC.

Membrane processes, including ceramic membranes, can also be considered as filtration processes. They are discussed in more detail later (Section 4).

3.2.3. *Available small-scale systems (SSS)*

Small-scale systems (SSS) are defined as systems of larger capacity than POU or POE systems, but smaller than centralized systems. Typically, SSS treat the water consumed by several families or a small village (around 1000 –10,000 l/day).

In principle, most of the POU methods described above can also be applied for SSS. Also technologies usually applied on a large scale may be adapted for decentralized or emergency use. For example, liquid chlorine or chlorine oxide dosage may be replaced by chlorine tablets or coagulant/flocculant mixing is conducted in pipes (Oxfam, 2001). Slow sand filtration is often used for community water treatment in DC often in combination with roughing filter, when maintenance or transport of chemicals is limited or not possible (Wagner and Lanoix, 1959; UNHCR, 1992; LeChavallier and Au, 2004). For example, the ICRC applied roughing and slow sand filters in Iraq as emergency systems (ICRC News, 2003).

3.2.4. *Areas of application of POU, POE and SSS*

The main reasons for and objectives of their applications, the types of water treated and the main initial requirements for successful installation and operation differ for POU, POE and SSS.

POU systems are represented by a variety of technologies for treating surface, ground- or rainwater, as well as poorly treated or stored tap water. Whether used in a traditional way (boiling), introduced by NGOs or the market, they are currently applied widely by households with different financial resources in DC, TC and sometimes even IC (Sobsey, 2002).

The necessary requirements for the successful application of POU treatment methods are the awareness of the population, the availability of information, low initial costs (for the local households) as well as low operational costs, simple maintenance and ability to control the efficiency of treatment.

POE systems are mostly used in IC; their application in TC and DC is limited to the supplementary treatment of tap or good quality well-water for the homes of rich people and hotels as well as childcare and medical institutions (Tsvetkova and Grinkevich, 2004). As they are often built on the basis of multi-stage treatment technology, qualified periodical control and maintenance are needed for their stable operation (Craun and Goodrich, 1999).

The most typical application of SSS in DC is for the community water supply (Pryor et al., 1998; Arnal et al., 2001; Burch and Thomas, 1998). However, in some cases SSS are used in the private sector of TC and DC for the production of bottled and treated water intended for water kiosks and private deliveries (Strikalenko et al., 1999). The availability of financial resources and organizational support are the critical factors for the construction and operation of SSS for the community supply, which also requires the involvement of NGOs, government or local community leaders. In both cases, qualified operation and maintenance are required to assure stable operation (Burch and Thomas, 1998).

In case of emergency, special SSS are already in use (Arnal et al., 2007). However, one of the main problems here is the response time of international organizations to deliver and install water-treatment material, which is normally around 10 days (Arnal et al., 2001). Container-based systems which do not require any on-site installation are consequently needed in these cases. POU systems are rarely applied in such cases, as the time and infrastructure needed for people to learn and adopt these methods are currently not available. However, some examples of successful applications exist, including distribution of hydration bags based on the forward osmosis principle (Cath et al., 2006).

3.2.5. *Dual water systems*

Although a centralized water supply system exists in many urban situations, the water quality may not be reliable for the reasons discussed in Section 2. A dual water supply system can make good sense in such cases.

In principle, two types of dual water systems exist:

Type I
Dual central treatment, dual distribution system: water of two different qualities is produced and distributed, one for drinking and one for general use.

Type II
Central treatment for household purposes, decentralized treatment for drinking water quality

As an example, the first concept (dual distribution systems) is used for the IJburg district of the city of Amsterdam in the Netherlands (Van der Hoek et al., 1999) and in Hong Kong (Tang et al., 2007). In the case of Rousehill (Sydney, Australia), recycled water from waste-water effluent is used for non-potable domestic sources (Law, 1996).

The second concept (central supply, decentralized treatment) was proposed for city of Daquing, China (Ma et al., 1998), with a population of 1 million. In this city, the costs and time frame required to improve the whole water supply system were considered to be unacceptably high, and a Type II dual water supply system was therefore proposed as an alternative. Decentralized "polishing" water-treatment plants (based on ozonation and membrane technology) fed with tap water were set up in seven of the city's districts for treating and distributing this 2.5–5% of the water. The distribution of treated potable water was organized separately with an independent network or with bottles (Ma et al., 1998).

Although a distribution system exists in Odessa, Ukraine, the water is not of drinking quality. The government has recognized that it is not feasible to improve the situation centrally and supports water kiosks instead. A large number of POU/POE systems are also applied (Strikalenko et al., 1999).

4. Membrane-based decentralized systems

4.1. *Membrane technology*

In general, membrane processes are characterized by the use of a semi-permeable film (membrane) and a driving force (Mulder, 2000). The driving force can be a difference in pressure, concentration, temperature or electric potential. Most membrane processes are pressure-driven and are commonly referred to as membrane filtration processes. In water treatment, however, electrically driven (electrodialysis) and thermally driven processes (e.g. membrane distillation) are also used. For POU systems, only membrane filtration processes are currently considered. The separation range of membrane processes is shown in Fig. 1.

As regards the production of drinking water, it is important to assess membrane technologies in relation to water-borne contaminants. The pore size of ultrafiltration (UF) membranes is small enough to ensure high log-removal of all kinds of microbiological hazards such as *Cryptosporidia*, *Giardia* and total bacterial counts (Hagen, 1998). Microfiltration (MF) is also claimed to have these properties, but some doubts have recently arisen with respect to bacterial retention by these membranes (Wang et al., 2007). Substantial virus removal can be attained with UF membranes since the size of viruses is in the range of 30–300 nm.

Nanofiltration (NF) and reverse osmosis (RO) can be used to remove inorganic contaminants from water. Most NF membranes are effective in removing bivalent ions (typical retention >90%), but RO membranes are required for monovalent ions. For example, desalination of seawater or brackish water is currently performed with RO membranes.

In comparison to conventional water treatment, the main advantages of membrane processes are that in principle water can be treated in one stage without chemicals or utilities, while the treatment footprint is relatively small. The developments in the membrane technology field during the last decades resulted in a significant decrease of

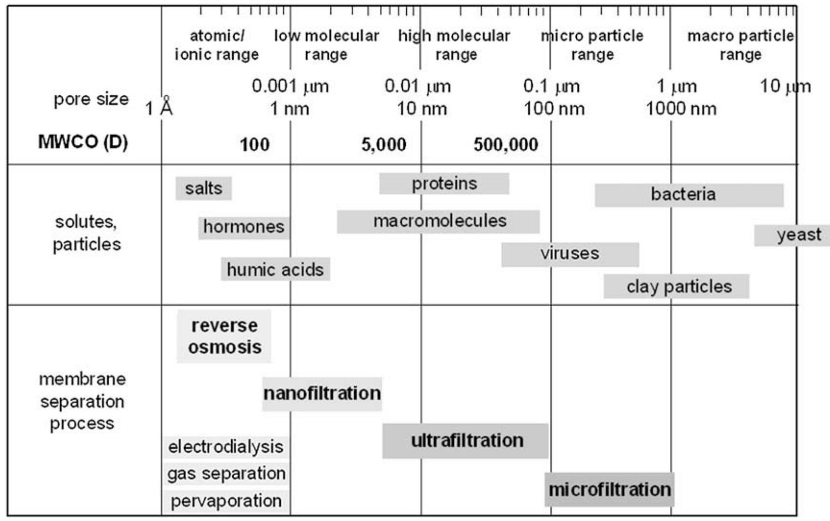

Fig. 1 – Membrane separation processes, pore sizes, molecular weight cut-off (MWCO) and examples of sizes of solutes and particles.

membrane costs and energy requirements (Churchhouse, 2000). In addition, membrane systems are built in a modular form which enables easy adaptation of process scale.

However, the main limitation of membrane systems is membrane fouling. Fouling prevention measures for MF and UF usually include regular backflushing (approximately every 30 min in large-scale applications) and chemical cleaning. In the case of NF and RO, pre-treatment is usually used, and the systems are being operated in a cross-flow mode. Such fouling prevention measures require automated process control and regulation, resulting in increased investment costs.

4.2. *Decentralized membrane systems available*

The same industrial-grade membranes used in large-scale water treatment plants around the globe have been incorporated into POU/POE water purifiers. They were developed for residential and small commercial/industrial applications. Initially developed in IC and for IC, these systems are being increasingly used in TC to improve the quality of available tap or groundwater.

The global directory for environmental technology (GreenPages, 2007) presents 531 companies (governmental and nongovernmental organizations, utility companies, importers, engineering consultants, etc.) working on the market or in membrane technology mostly in IC and TC. At least a quarter of them produce, import or provide services involving POU/POE membrane-based systems. Small-scale systems also employ similar membrane processes as for large-scale applications. Many of these systems were initially developed for emergency water supply, but systems are also available that are specifically designed for remote areas in DC and TC (Hoa and Lesjean, 2008). As the literature presents only limited systematic data on these kinds of systems, the overview presented below is based mainly on market information and reports of NGOs.

4.2.1. *RO-based systems*

Most commercially available POU systems in IC use reverse osmosis membranes as a key element of water treatment. In general, RO-based POU water treatment is a multi-stage process that includes pre-treatment and post-treatment stages in addition to an RO spiral-wound membrane module (AMI, 2007; AMPAC, 2007; APEC, 2007; Fountain Softeners, 2007; Novatec, 2007; WESE, 2007; WGSI, 2007).

Typical pre-treatment stages include sediment filters or microfilters and activated carbon. Post-treatment stages used in the system also include activated carbon filters. Such systems are normally installed to purify tap water from a centralized supply in IC, and can be placed under a sink in a kitchen. They work without an electricity supply, the necessary pressure being provided by the feed tap water in the system. The maintenance of the system in most cases requires the replacement of pre- and post- filters once in 6–18 months, while membrane lifetime is 2–3 years. The price of the system varies according to the flow rate in the range from US$ 200 to 700 (APEC, NOVATEC, AMI membranes, etc.). Their annual operation costs are approx. US$ 85–135.

Being designed to treat tap water in IC, most systems also have limitations with respect to the allowable feed water quality. In general, these kinds of multiple-stage RO systems are complex and relatively expensive installations that require service and replacement of parts and a defined source-water quality. So their application in DC is not realistic even if they are widely used and accepted in IC. However, these systems can be increasingly found on the market in TC for secondary treatment of tap water.

An RO-based system designed to be used independently of energy sources was developed by Schafer and Richards, 2005. This "ROSI" system is designed to treat water from a variety of sources, ranging from highly turbid surface waters to highly saline brackish waters. The filtration process consists of two stages – the pre-treatment stage using an ultrafiltration membrane is followed by the desalination stage using an RO or NF membrane. The UF membrane removes most pathogens such as bacteria as well as particles and some colloidal material, thus protecting the RO/NF membrane from excessive fouling, in particular bio-fouling, and reducing the cleaning frequency of the modules (Schafer and Richards, 2005). Being equipped with photovoltaic or solar modules, the ROSI system may be used independently of any energy sources in regions with a high sunshine intensity. The ROSI system was tested in remote rural areas in Australia. There are no published data on the costs of this system. The equipment is relatively complex, including UF, RO and photovoltaic modules. Therefore, the investment costs are expected to be high, and maintenance is required by qualified personnel.

Reverse osmosis technology has also been used for brackish or sea water desalination in emergency situations. There are few systems available from different producers (Emergency Seawater 800, (Big Brand Water Filter, 2008); MORO AQUAMOVE (Elga-Berkefeld, 2008); GE Emergency RO (GE, 2008), etc.). Generally, these systems are driven by electricity or gasoline engines, and are equipped with several pre-treatment stages (Sediment filtration, MF, UF). The systems require relatively good raw water, are relatively expensive (approx. US$ 10,000) and require maintenance, which considerable limits their application.

An example of application of forward osmosis for POU water treatment in emergency situations is a hydration bag (Hydration Technologies, 2008). In the hydration bags, a consumable draw solution (e.g. sugar or beverage powder) is packed in a sealed bag made of semi-permeable forward osmosis membrane. Upon immersion of the bag, water diffuses through the membrane due to the osmotic pressure difference and dilutes the initial solution. At the end of the process, the diluted draw solution may be consumed as a sweet drink containing nutrients and minerals (Cath et al., 2006).

4.2.2. *UF-based systems*

As pointed out above (Section 2.1), most water-quality problems are due to pathogens, which are completely retained by ultrafiltration membranes (see Fig. 1). Moreover, these membranes require significantly lower pressures than RO membranes, due to the latter's higher resistance and because RO generates an osmotic pressure which counteracts the water transport through the membrane. Nevertheless, POU systems based on ultrafiltration technology are not used widely for treating household drinking water. Some POE technologies are available on the market, and some of them also have a pre-treatment stage and hollow-fiber membrane modules.

One of the few UF-based POU systems existing is LifeStraw Family from Vestergaard Frandsen (LifeStraw, 2008). The system consists of a UF module (20 nm pore size), a pre-filter for reducing turbidity and a chlorine chamber. A feed water tank, connected to the module by a flexible hose, is placed elevated to create a pressure of 100–150 mbar. The module has to be manually backwashed once in 1–2 days. A first assessment of LifeStraw Family by the University of Arizona showed stable operation and high efficiency of bacteria and virus reduction during filtration of 18,000 l of water (turbidity 100 NTU, TOC 10 mg/l) with a final flow rate of 6–8 l/h. The system is currently being tested in Congo and China.

One of the most widely used in IC and TC home tap water-treatment systems based on ultrafiltration POE and suitable for a wide range of feed water qualities is Homespring® developed by Zenon (Homespring, 2007). This kind of system is supposed to provide good quality water to the whole home (POE). It also includes a pre-treatment stage with an activated carbon filter. The hollow-fiber ultrafiltration membrane is a key part of the system, supposed to remove bacteria, cysts and viruses. The system is designed to treat surface, well or tap water without any other pre-treatment. Homespring is intended to be used with existing pressures (e.g. from the tap water) and requires annual maintenance. The carbon filter capacity is the limiting parameter of the process capacity and the filter needs to be replaced once a year. These systems are designed to provide a continuous flow of 14–17 l/min, or approx. 840–1020 l/h (20,160 –24,480 l/day).

Another domestic POE UF system, manufactured by MEMFIL, is available on the market in Malaysia, China and Singapore. According to the information given by the manufacturer (MEMFIL, 2007), this system is also based on a hollow-fiber module but is designed for higher flows from 1500 to 3000 l/h (36,000–72,000 l/day). Its operating pressure varies from 1.5 to 3.5 bar and either tap pressure or a pump should be used. The peculiarity of this system is that it normally needs backflushing only once a week, which should be done manually by the household through closing and opening some valves (in large-scale application UF membranes are usually backflushed every 30 min). It also has a limitation on raw water quality: the source-water turbidity should not exceed 20 NTU. It is normally used for the additional treatment of tap water or for deep groundwater wells.

From the limited information available, the module available from a Malaysian company, Hezong Trading Sdn Bhd (Hezong Traiding Sdn Bhd, 2007) appears to be very close to the MEMFIL® system. However, it has a flow rate of 2200 l/h (52,800 l/day) and operates only on tap water.

Three low-pressure ultrafiltration membrane systems have been tested in South Africa for community water supply (Pryor et al., 1998; Jacobs et al., 2000, 2004). They were tested on surface waters containing high levels of suspended matter and occasional occurrences of algal blooms and diffuse pollution caused by surface runoff into the rivers. The plants were designed to supply 10,000 l/day of treated water in cross-flow mode and required regular cleaning. Detergent and complexing agents were used to clean the system when operating on waters with a high organic load, whereas sodium hypochlorite was used when the plant operated in conditions of lower organic pollution. The low plant operating pressure of 100 –150 kPa enabled the process to be applied to rural and peri-urban applications by utilizing the head of water without the need for a feed pump. A recycle pump was used in these pilot plants, so that an energy source (electricity) is required (Pryor et al., 1998; Jacobs et al., 2000; Jacobs et al., 2004).

Arnal et al. (2001) proposed an ultrafiltration module also suitable for application to urban supply systems in developing countries. The proposed membrane module has a treatment capacity of 1000 l/day when operating at maximum efficiency and the number of modules can be extended, with a consequent increase in the treated product flow, adapted to the specific case and demand. The module is equipped with a polysulfone spiral-wound membrane with a molecular weight cut-off of 100 kDa. Before the feed water enters the feed tank of the UF facility, it is first pre-treated in a series of different filtration units:

- coarse filter
- microfilter (500 μm)
- security filter (5 μm)

The equipment was modified to supply water directly from a source to small geographically isolated communities with no water or electricity supply. The module was equipped with a manually operated wheel whose rotation produces energy for the pump. This manual ultrafiltration plant can provide water for direct consumption of up to 300 persons when working at top efficiency (Arnal et al., 2001, 2002, 2004). The projected manual plant does not require any fuel or additional power source, thus facilitating its application, and has a compact design to assure easy handling and transport (Arnal et al., 2001).

A similar UF small-scale plant has been installed in Ecuador for supplying the local community with water. Its production capacity is 480,000 l/day and it was designed to work only on hydrostatic pressure. A sand filter and a 50 μm pre-filter are used for the pre-treatment. The water from this plant is also used for the production of milk and meat-based products by a local agro-company (Arnal et al., 2007).

Skid-mounted or container-based systems are available for the continuous production of drinking water or as an emergency solution (e.g. floods, hurricanes). These small-scale systems, available from producers such as Opalium (France) (Opalium, 2007), can be equipped with MF or UF membranes, depending on the application, and are adapted to a wide range of source-water qualities, including surface waters with high NOM concentrations. The UF membrane modules of the OPAMEM type (Opalium, 2007), developed by Opalium (France), are hollow-fiber modules with a nominal pore size of 0.01 μm, made from chlorine-resistant polyethersulfone. The unit operates in dead-end or cross-flow inside–outside mode with backwashing for cleaning and has a capacity of up to 5,760,000 l/day per unit.

The Perfector-E® water purification system from X-Flow (NORIT, the Netherlands) was specially designed for supplying water to the tsunami victims in Asia by treating heavily polluted surface water. According to their information (X-Flow, 2007), it uses a two-stage pre-treatment process consisting of a coarse filter and two parallel micro-strainers. The main treatment stage consists of two UF dead-end modules operated with backflushing as well as an optional UV disinfection barrier. The system may be operated by unskilled personal but is rather expensive (approx. US$ 26,000).

There are also examples of using UF units as a pre-treatment stage for NF or RO treatment. The ROSI system, developed by Schafer and Richards, 2005, is described in Section 4.2.1.

4.2.3. MF-based systems

Ceramic microfiltration is among the few membrane technologies applied in DC and recommended by the WHO (Sobsey, 2002). Most ceramic MF membranes are available in the form of monoliths or hollow cylindrical tubes and have a nominal pore size of around 0.2 μm (Clasen et al., 2004). Due to its pore size, such filters provide complete protection from bacteria, but only partial protection from viruses (size range of 30–300 nm). Filters produced and distributed in DC are normally in the form of pots (e.g. clay pots) and their pore size is larger, normally reaching 0.6–3.0 μm (Lantange et al., 2007). As filterable bacteria range well below 0.6 μm (Wang et al., 2007), size exclusion alone in principle cannot provide a complete disinfection with this kind of filter. Many commercially produced ceramic filters are impregnated with colloidal silver to act as an additional disinfection step and prevent biofilm formation on the filter (Sobsey, 2002). Pore constriction or cake layer formation can be an additional mechanism of removal. Thus, the efficiency of removing bacteria depends on the filter configuration and the mode of production. Filters produced in IC generally show superior performance in removing bacteria and viruses than those produced in DC (Sobsey, 2002). The rate of bacteria removal by the ceramic filters distributed widely by ‘‘Potters for Peace’’ reaches 99.99% in laboratory tests, for example. However, their effectiveness in inactivating and removing viruses is unknown and their performance in field applications has not been evaluated (Lantange et al., 2007).

Microfiltration is being increasingly used in POU systems developed in IC for travelers from the IC. One of the best known systems is produced by Katadyn, Switzerland. The filters consist of a ceramic 0.2 μm membrane, and are operated by gravity or a hand pump. These portable systems may also be used on turbid water and water polluted with organic matter , but their lifetime is limited to 20,000 –100,000 l of filtered water depending on raw water quality and type, and the costs are relatively high (US$ 250–600).

A new application of microfiltration is the ‘‘FilterPen’’ from the FilterPen Co of New Zealand and Filtrix Co of The Netherlands (Filtrix, 2007). The concept of ‘‘point-of-use’’ is applied here in its most decentralized form, whereby the source water is sucked through a straw-like device which is actually a microfiltration membrane. The membrane has an average pore size of 0.15 μm and a surface area of 0.02 m^2. Initial (clean water) flow rates are about 0.1 l/min at a pressure difference of 0.1 bar. According to the manufacturer's data, depending on the feed water quality, the service life is approximately 4 weeks or 100 l of treated water (which corresponds to water production of about 3.5 l/day). The membrane material is a blend of different polymers (PES, PVP and PP). Filtrix has been developed for travelers from IC going to DC, and is now also used by the German Military based in DC.

LifeStraw Personal is a similar product by Vestergaard Frandsen developed for personal use for people in DC traveling away from home for long periods of time (e.g. shepherds). The original purpose of this membrane filter was to protect people from Guinea Worm Disease, however, the filter showed also Log 6 efficiency in removal of waterborne bacteria and Log 2 efficiency against viruses. The life time of the LifeStraw is limited to the filtration of approx. 700 l of water.

SkyHydrant unit (SMF-1) developed by SkyJuice Foundation (Australia) is intended for community water supply in DC and disaster relief applications. This process combines MF (membrane pore size of 0.1 μm) with chlorine disinfection, and may be operated on hydrostatic pressure of at least 30 mbar. The membrane has to be backflushed manually every 1 –12 h depending on the water quality, and regularly washed with 10% hypochlorite solution. Thus, the system requires a more or less skilled operator. SMF-1 is adapted to highly turbid waters (max 500 NTU) and has been implemented in approx. 10 countries in South East and Central Asia and South America (SkyJuice, 2008).

Microfiltration was combined with biological degradation in a membrane bioreactor for producing drinking water from contaminated surface water sources by Li and Chu (2003). Membrane bioreactors are normally applied for waste-water treatment, but in this case a drinking water application was investigated. The process was found to increase the biological stability of the water as well as to reduce the trihalomethane formation potential. The process was operated for 500 days with three chemical cleaning steps and weekly physical washing (Li and Chu, 2003). However, the process has not yet been tested in DC .

Woven filters based on fine polyamide fibers were developed by Pillay (2006). Because the spaces between the fibers are in the range of micrometers, this material could be considered as a microfiltration membrane. The materials and production costs are relatively low, which in principle makes their application suitable for the poor. Cleaning can be carried out mechanically or by drying combined with mechanical cleaning, as the sheets are resistant to wear and insensitive to drying. Development and characterization of these sheets is currently in progress, but their ability to retain bacteria has not yet been confirmed (Pillay, 2006).

A fast response emergency water treatment unit has been developed also at the University of Kassel (Frechen, 2007). The MF membrane module is driven by gravity, is chemical free, may be carried by one person (<25 kg dry weight) and operated by non-trained persons. It is intended to treat highly polluted water for 200–500 people during the first 5–10 days after a disaster. The main idea behind this system is to provide simple water treatment to cover the time gap until disaster relief teams are able to deliver, install or repair long-term drinking water supply systems (Frechen, 2007).

5. Suitability of decentralized systems for developing and transition countries

5.1. *Evaluation of decentralized systems*

In Section 3.2.2, the performance criteria for decentralized systems (including POU, POE and SSS) were discussed. In Table 1, the available decentralized systems are evaluated against these criteria. The upper part of Table 1 summarizes systems for DC, while the lower part represents systems mainly developed and used in IC and TC (including membrane systems). The meaning of the symbols in Table 1 is explained below.

Performance: "++": the water produced is microbiologically safe according to WHO standards if the treatment is performed correctly; "+": water produced by the system is safe only under certain conditions (e.g. if raw water is not turbid) or the system is efficient against most of the pathogenic microorganisms with few exceptions.

Ease of use: "++": daily operation is limited to filling in of raw water and collection of treated water; "+": requires additional (time consuming) operations which, however, may be performed by unskilled person with no or little training.

Sustainability: "+": system may be produced locally from locally available materials, with limited use of chemicals and non-renewable energy; "−": system requires chemicals or non-renewable energy sources for daily operation; "− −": widespread application causes or may cause in future significant environmental damage (e.g. deforestation due to boiling).

Social acceptability: "++": application is based on tradition or it is already in use; "+": available studies showed good social acceptance; "+/−": available studies are contradictory, or the results depend on the region studied.

The investment costs listed in Table 1 generally include the costs needed to buy, deliver and install the system. The operational costs include the costs of reagents, energy and servicing if needed, as well as maintenance and replacement of parts of the system. The World Health Organization (WHO) categorizes costs for POU systems as low, medium and high on a worldwide basis that includes the poorest people. The categories for annual household cost estimates in US dollars are less than US$ 10 for low, US$ 10–100 for moderate and >US$ 100 for high. These cost categories will clearly be different for different economic situations in various regions and countries of the world (WHO, 2002). Nevertheless, we will use them further to compare the various systems.

Only few of the available POU technologies (SODIS, biosand filters and free chlorine) can fulfill the low-cost requirements for DC and provide an acceptable water quality if operated correctly. The costs of most of the POU technologies are in the moderate range and may be affordable to households in TC and some households in DC.

Some of the available systems are widely used, although they may not always be the optimal solution. For example, boiling with fuel is widespread but is not very sustainable and leads to uncontrolled air pollution and deforestation. A problem with chlorination is that the motivation to apply it is generally low because of the bad taste and smell of the resulting water. Other technologies are not effective for all water qualities, thus UV treatment is not very effective for surface waters with high turbidities. Furthermore, the investment costs for UV systems are high and they require a reliable supply of electricity.

Most of the low and moderate cost POU technologies listed require everyday handling (SODIS, chlorination, combined coagulation with filtration and chlorination), while the others need monthly or annual maintenance (activated carbon filters, BSF, UV) or require the availability of spare parts and a certain level of education and training for their servicing. Time-consuming or complicated maintenance is one of the main problems limiting the application of available POU technologies.

Some of the systems described can also be used on a community scale. One of the examples is slow sand filtration. This technology is cheap and may be completely built from locally available materials, however inadequate maintenance is often a main reason of system malfunction or

Table 1 – Overview of available POU/POE water treatment technologies for DC, ICs and TC.

Water treatment system	Type of supply	Estimated costs		Evaluation criteria						Source
		Investment $US	Operational $US[a]	Performance	Ease of use	Maintenance	Sustain-ability	Dependence on utilities	Social acceptability	
Developing countries										
Boiling with fuel	POU	Cook pot	Depends on fuel price	++	+	Depends on fuel availability	–	Fuel	++ tradition	Sobsey, 2002
Solar disinfection	POU	Plastic bottles	None	+, when low turbidity	+	Regular, time consuming	+	None	–/+	Sobsey, 2002
UV disinfection with lamps	POU	100–300	10–100	+, when low turbidity	+/training required	Cleaning, annual replacement	–	Electricity	+	Sobsey, 2002
Free chlorine	POU	2–8 (vessel)	1–3	+	+	Regular	–	None	Taste problem	Sobsey, 2002
Biosand filters	POU	10–20	None	81–100%, viruses – ?	++	Required once in few month	+	None	+	Kaiser et al., 2002
Ceramic filters	POU	10–25	None–10	+/viruses – ?	++	Cleaning, replacement	+	None or tap pressure	+	Clasen et al., 2004
Coagulation, filtration, chlorination	POU	5–10	140 220	+	+/training required	Regular, time consuming	–	None	Taste problem	Sobsey, 2002
Transition and industrialized countries										
Activated carbon filtration	Faucet-mounted	25–50	25–50	+ if replaced	++	Annual replacement	+	Tap pressure	+	WSC, 2007; Ecosoft, 2007; WSC, 2007
	Under a sink	50–300	50 100							
	POE	500–800	n.a.							
Microfiltration[b]	POU	3	12	+/viruses – ?	+/++	Cleaning, replacement	–/+	None	–/+	LifeStraw, 2008; Li and Chu, 2003; Pillay, 2006
	SSS	n.a.	n.a.							
Ultrafiltration	POU	40	None	++	++	Backflushing	+	Gravity	+	LifeStraw, 2008; Homespring, 2007
	POE	2700–3000	n.a.			Cleaning replacement		Tap pressure or electricity		
	SSS, 250–1000 people	178000	n.a.							
Reverse osmosis	Single tap	300–600	80–120	++	++	Required annually	–	Tap pressure or electricity	–/+	WSC, 2007; AMPAC, 2007; Schoeman and Steyn, 2003
	SSS, 50 m^3/day	29900	9000							
Bottled water	For a family of 4 people per year	None	360–720	Depends on the region	Depends on delivery distance	None	–/+ when in own bottles	None	+	WSC, 2007

n.a., data not available.
a Operational costs for POU/POE systems are given for a family of four.
b Ceramic filters are considered separately.

breakdown. UV lamps are also used in multistage small-scale systems for disinfection (Triangular Wave Technologies, 2008). Also this technology requires a high level of maintenance which limits its suitability for POU application.

Table 1 shows that an ‘‘ideal’’ solution, namely one whose maintenance is limited to the delivery of water and whose costs are low, does not yet exist for POU systems. This may explain the low success of these systems so far. Therefore, further development is needed to simplify the maintenance of existing low-cost systems or reduce the costs of more advanced ones.

For the situation in the IC and TC, the costs of most solutions including membranes can be considered appropriate for middle-income households. Factors limiting their application in TC and remote areas of IC are the annual maintenance, the level of education necessary to operate the systems correctly, and feed water quality. Moreover, most systems rely on tap pressure and external energy sources (electricity), which may be not available in TC.

The investment costs of SSS are generally too high for communities in DC and TC. These communities also lack trained personnel to maintain these systems and often do not want or cannot assume the responsibility for their performance after their construction by the government or NGOs. The provision of regular maintenance by regional maintenance centers, such as is practiced in some regions in South Africa, needs a certain organization and control and would not be possible in many other countries. There is also a need to develop robust, reliable and easy-to-maintain technologies for community supply systems for DC and TC.

5.2. *Available membrane systems for decentralized application in DC/TC*

A whole range of membrane systems relying on tap water and tap pressure is available for POU applications, but they are not directly suitable for DC/TC not only because tap pressure and pre-treated (tap) water are not available, but also for financial reasons as mentioned in Sections 4.2.1 and 5.1. Consequently, these systems are not discussed here.

Table 2 summarizes the available membrane systems that do not rely on tap pressure and do not have significant limitations on feed water quality. The possibilities for stand-alone operation of these systems are limited, because most of them require supervision and/or maintenance (e.g. cartridge replacement).The evaluation criteria discussed above for decentralized systems in general, also apply for membrane-based systems, however some of the criteria have to be discussed in more detail. The technical complexity of the available system varies quite substantially. Some processes consist of a membrane treatment unit only, others also include pretreatment or post-treatment steps. This influences the system complexity, investment and maintenance. Furthermore, the required energy supply differs among the systems. An important additional criterion for membrane systems is the acceptable feed water quality and the possibility to deal with varying feed water quality as is the usually the case with surface waters. Systems which are designed to operate on tap water quality only will therefore not be suitable for such applications. Finally, the energy concept is of importance. Some systems rely on tap water pressure, while other systems require electricity or solar power, and some systems work on gravitational pressure.

Table 2 summarizes these criteria as well as the capacity, and the application area for which the system is intended.

For an effective long-term operation, rare but regular maintenance is needed (chemical cleaning, UV lamp replacement (Norit), repair of pumps and energy suppliers), which may be not always possible in DC or emergency situations. The systems working on hydrostatic pressure (gravity) are generally simpler. However, except for the disposable systems (FilterPen), these systems require everyday supervision and/or maintenance (e.g. manual backwashing). In addition, most available membrane systems need periodic cleaning with chemicals that have to be transported and stored. Depending on the type of chemicals and their amounts, skilled personnel are needed in order to prevent the risks associated with the handling of chemicals.

The costs of many of the systems listed are not yet known because they are still in a state of development and are not available on a commercial scale. In general, however, it can be stated that the investments for pumps, solar-powered systems and measurement & control systems are high, so that many of the systems listed will not be affordable for people with low or middle incomes. However, the cost of the membrane itself should not be prohibitive for a POU application: UF membrane costs are currently around US\$ 40 /m^2 and declining. Furthermore, the permeability of UF membranes is relatively high with clean membrane permeability in the range of 500–1000 l/m^2 per h per bar. Also if only a fraction of the clean membrane permeability is assumed for long-term continuous operation, the required membrane surface for a POU application is low. For example, assuming 5% clean water permeability at 0.2 bar would give water production of 5 l/m^2 per h or 10 l/m^2 per h. Considering that only 20 –50 l/day is required for a POU application, the membrane area needs to be only 0.17 –0.42 m^2, corresponding to US\$ 7 –17 per family per system. The annual costs of the system will depend on the service life of the membrane.

For POU systems, the membrane life time is indicated as the volume of water that can be filtered until the filter gets clogged. This volume is dependent on feed water quality and the membrane surface. For example for LifeStraw Family this volume is estimated to be 18,000 l of filtered water (basic water quality parameters: turbidity 15 NTU and TOC 5 mg/l). Assuming a daily drinking water consumption of 20 l, this corresponds to approx. 2.5 years of operation. The average service life of a clay pot is approx. 6 months. Personal-use devices are able to filter from 100 l (Filtrix) to 700 l (LifeStraw Personal) of water, which corresponds to 1–7 months of use. In contrast to POU systems, which are mostly designed to be disposed of once they are clogged, the membrane used in SSS may be cleaned in or out of the module with chemicals that may restore its permeability. Thus, we can expect a longer membrane service life. For example, the membrane service life for SkyJuice is indicated to be approx. 2 years in DC.

Thus, assuming that the average membrane service life in DC is several years, the membrane costs themselves are relatively low and affordable even for the very poor (based on the assumptions above and a service life of 2 years, the membrane

Table 2 – Available membrane systems for decentralized application in DC/TC and their properties.

Membrane system		Capacity (l/day)	Pre-treatment (post-treatment)	Feed water quality	System investment costs ($)	Maintenance/ operation	Energy	Application
RO, POU	Tabletop or under a sink systems	145–340	MF, activated carbon, multistage	tap water	ca. 400	Cartridge replacement 2 times per year	Tap pressure	IC/TC, applied
RO, SSS	ROSI	1000	UF	Brackish water	High	3 cartridges, 1–2 times per year	Autonomous (solar energy)	DC, tested
	Emergency Seawater, Aquamove, etc.	720000	MF/UF	Sea or brackish water	ca. 10000	Requires operator	Fuel or electricity	Emergency, applied
FO, POU	Hydration bags	3 (9 L/system)[b]	None	Surface water	30	None	Osmosis pressure	DC, emergency
UF POU	LifeStraw Family	20–30, 18000 l/system[b]	Chlorine	Surface/groundwater	ca. 40	Daily backflushing	Gravity	DC, tested
UF POE	Homespring, POE	25000	Active carbon	Tap or groundwater	2700–3000	Cartridge replacement; annual maintenance	Tap pressure/ electricity	IC/TC applied
UF SSS	Homespring, SSS	60000 240000	None None		141000 178000			
	"Arnal" system	1000[a]	– Coarse filter – Microfilter – Security filter	Surface water	n.a.	n.a.	Manual rotation wheel	DC, tested
	Skid-mounted systems	≤6000	Different configuration	Surface/groundwater	Depending on lay-out	Depending on lay-out	Depending on lay-out	DC, emergency, applied
	"Pryor" system	10 m^3/day	None	Surface water	n.a.	Chemical cleaning	River flow and electricity for the recycling pump	DC, tested
	Perfector E (Norit)	48000	Multistage MF, UV	Brackish water	ca. 26000	Maintenance on a long term	Fuel	Emergency, applied
MF, POU	FilterPen	100 l/system[b]	None	Surface water	49.95	(Disposable product)	Human power (suction)	DC, applied
	LifeStraw Personal	700 l/system[b]			3			
	Ceramic filters (pots)	ca. 5000 l/system[b]	None	Surface water	10–25	None or cleaning	Gravity	DC, applied
	Ceramic candles	10000 l/system[b]			150–300	None		
	Katadyn	100–750 l/system[b]	MF, active carbon		200–400		Manual pump	
MF, SSS	SkyJuice	10000	None	Surface/groundwater	ca. 1000–2000	Manual backflushing and cleaning	Gravity	DC, applied
	MBR based	n.a.	None	Surface water	n.a.	Chemical cleaning	Electricity	DC, tested ?
	Skid-mounted systems	≤5760000	Different configurations	Surface/groundwater	Depending on lay-out	Depending on lay-out	Electricity	DC, emergency applied

n.a., data not available. The literature references for this table are discussed in the text, the data on costs and capacity for the market products were obtained from the producer.
a Capacity per membrane module.
b Capacity per system service life.

costs are $ 0.8–2.2 per person per year). In addition to the membrane, however, a system is required to operate it, and in some cases pre-treatment may be required. The total costs of the system will depend on the sum of the investment costs of its components and the operating costs, including membrane replacement costs. Among all the systems listed, only the investment costs of LifeStraw Family and SkyJuice are in the range of affordability for DC (LifeStraw Family is approx. $ 2.5–3 per person per year for drinking water; SkyJuice is $ 3–4 per person per year for water for basic domestic needs).

5.3. *System requirements for decentralized membrane systems*

Table 2 summarizes systems on RO, UF and MF. RO systems, which intended to be used for desalination, require high pressures and therefore depend on cost- and maintenance-intensive pumps. UF and MF based systems are intended for disinfection purposes. It should however be noticed that due to the pore size of MF membranes, no complete protection for viruses can be provided (see Section 4.2.3). Considering the fact that a large number of diseases can be transferred by waterborne viruses (e.g. Adenovirus, Enterovirus, Hepatitis A ; see WHO, 2004b), the use of MF membranes brings important limitations. Furthermore, the size range of ceramic pots is less defined and, depending on the production process and operation, no complete protection against bacteria can be provided. In view of these limitations, we will confine the discussion below to UF membranes.

For application in urban areas of DC and TC, decentralized systems evidently should be low cost and low maintenance. If tap pressure is available, this provides a free form of energy to drive membrane processes, and is the preferred option. However, no such systems seem to be available on the market that are specifically designed to meet the cost criteria for developing countries. If no tap pressure but partially treated water is available, a hydrostatic pressure or a pump can be applied. A disadvantage of pumps however is the need for maintenance and spare parts. Thus, in view of these criteria, the LifeStraw Family appears to be a suitable POU system for this type of application. However, no SS system meeting the above-mentioned criteria seems to be available.

For application in rural areas of DC, systems should be able to operate with untreated surface water, and should be independent of electricity or tap pressure. Systems that operate with surface waters do not necessarily work trouble-free with other water qualities. As generally known, membrane processes can easily clog due to fouling factors, which are mainly related to NOM fractions and inorganic compounds (e.g. Fe, Mg). Long-term test results with a broad range of feed water qualities should be available in order to be able to predict the performance in every possible situation. In a large number of cases therefore, a pre-treatment step may be required. However, pre-treatment processes increase the costs and chance of failure of the systems, and the whole system finally should meet the low-cost and low-maintenance criteria. Therefore a clever design and extensive practical testing of such systems is essential for success.

As pointed out before, a critical aspect of membrane based SSS and POU systems is the operation, maintenance and control. Most of the currently available membrane systems need regular flushing, backflushing and chemical treatment (see Table 2). Systems equipped with automatic flushing and cleaning however require complicated instrumentation and use chemicals that must be transported, stored and handled. This makes them less suitable for use in DC and TC. The solution should be sought in ‘‘low-tech’’ systems that can be operated intuitively and controlled by the local population.

Membrane fouling itself is an indicator of the system performance: once a membrane is clogged, a household or an operator is forced to act and clean or replace the membrane. However, the system integrity is a critical factor of polymeric membrane filtration. Membrane integrity tests cannot be done at low cost and by untrained personal, thus increasing the risk of unnoticed system breakdown. However, the membrane surface may be protected by installation of a simple particle screen and limiting access of untrained people to the membrane surface. In addition, central monitoring systems can be installed which activate an alarm when the installation operates beyond its specification. SSS can then be run unmanned and a large number of installations can be controlled by a single centralized expertise center.

In summary, the following research and development needs exist for membrane-based decentralized systems:

- Development of membrane systems operating on tap pressure for treatment of tap water in urban areas, which meet the cost criteria for DC
- Development of UF-based SS systems using hydrostatic pressure
- Long-term tests of membrane systems with a wide range of feed water qualities to enable prediction of process performance depending on the local conditions
- For highly fouling feed waters: the development of efficient and robust pre-treatment processes for membrane systems and the integration of such pre-treatment processes with the membrane step
- The coupling of decentralized membrane systems with centralized supervision and service centers
- Systems requiring low maintenance and control, which can be operated by the local population

The recent development of a few membrane-based decentralized systems seem to fulfill at least part of the criteria for applications in DC. This underlines the high potential of membrane technology in this field. However, better understanding of the membrane fouling processes and further developments are needed in order to develop systems that fulfill most of the criteria thus enabling gradually increasing implementation. By joining efforts in this direction, membranes could contribute substantially to solve the tremendous problems associated with drinking water as outlined in the Millennium Development Goals.

6. Conclusions

A huge effort is required in order to reach the drinking water objectives set out in the Millennium Development Goals, and so far a centralized treatment approach has not been very successful in this respect. In rural areas, problems occur because the entire population is not connected to a water supply system. Moreover, available central systems are often not maintained properly and fall into disrepair. Urban areas face high population growth rates in many areas, especially in Asia and sub-Saharan Africa. In many cases, informal settlements appear which are not or only partially provided with safe drinking water. Even in urban areas where a water supply is available, the quality of the tap water is often unreliable, and decentralized systems are being installed by those who can afford it.

In order to cope with insufficient water quantity, groundwater wells are installed by the population or rainwater is harvested. In both cases, the water quality is very dependent on the local conditions, so that the water is not safe to drink in all cases.

A range of decentralized systems is available to cope with water quality problems. The focus of this review is on decentralized systems. Decentralized systems include point-of- use (POU) systems, which are defined as systems which treat only the potable (drinking and cooking) water of one household, corresponding to approximately 25 l/day, point-of- entry (POE) systems, defined as systems to treat all the water entering a house, and small- scale systems (SSS) used for community water treatment or in emergencies. POU systems generally employ the following treatment principles: heat and/or UV, physical removal processes and chemical treatment. Small- scale systems in general employ similar processes as in large-scale water treatment plants.

Performance criteria for decentralized systems in DC and TC include ease of use, low maintenance, the independence on utilities (energy and chemicals), and low costs. Many systems are available which meet several of the criteria, but not all the criteria at the same time, which may explain the moderate success of the technologies so far.

Decentralized membrane systems can be based on microfiltration (MF), ultrafiltration (UF) or reverse osmosis (RO). RO-based systems are mainly intended for desalination purposes. RO requires relatively high pressures and therefore the process is dependent on cost- and maintenance-intensive pumps. MF- and UF-based systems are intended for disinfection. Not all available MF filters however have pore sizes enabling complete removal of bacteria. Moreover, the pore size of MF is by definition too large for complete removal of viruses. Therefore, MF-based systems can only provide partial protection against viruses. Several UF-based systems are on the market or in development. Some of these systems seem to meet the low-cost and low-maintenance criteria and some of them are operating on hydrostatic pressure, thus avoiding the need for pumps and additional energy sources. Only one POU system and no single SS system seem to meet all the criteria. Thus, efforts are required to develop POU processes meeting all the performance criteria. From the literature only limited data are available on the long-term performance with all possible water qualities. Considering the high fouling capacity of certain water types, the introduction of appropriate pre-treatment processes should be considered.

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