1. Introduction

1.1. Background

A large proportion of the World's people do not have access to improved or microbiologically safe sources of water for drinking and other essential purposes: (WHO/UNICEF, 2000) has estimated that 1.1 billion people do not have access to “improved drinking-water sources”. Consumption of unsafe water continues to be one of the major causes of the 2.2 million diarrheal disease deaths occurring annually, mostly in children (WHO/UNICEF, 2000).

Despite major efforts to deliver safe, piped, community water to the World's population, the reality is that water supplies delivering safe water will not be available to all people in the near term (Argawal et al., 1981; Feachem et al., 1978; IDRC, 1980). The millennium declaration established as a goal halving the proportion of the global population without access to safe water by 2015. One reason for this is that fecal contamination of source and treated water is a persistent, worldwide problem. Sanitation coverage is inadequate in many parts of the world and is likely to persist for the foreseeable future. Fecal contamination of source and treated water is further exacerbated by increasing populations, urban growth and expansion, peri-urban settlement and continued and perhaps increasing pollutant transport into ground and surface water due to deforestation, global climate change, recurrent disastrous weather events (hurricanes, cyclones, floods, tsunamis, etc.) and increasing coverage of the earth's surface with impervious materials.

Current estimates of the number of people using microbiologically unsafe water are probably low. This is because the assumptions about the safety or quality of water based on its source, extent of treatment or consumer handling do not take into consideration several well-documented problems. One problem is that co-called protected or improved sources, such as boreholes and treated urban supplies, can still be fecally contaminated and deliver microbiologically unsafe water. In some cities the water systems abstract unsafe water from unprotected or contaminated sources and deliver it to consumers with no or inadequate treatment, yet these water systems are classified or categorized as improved and safe. Another problem contributing to the underestimation of the population served by unsafe water is contamination of water during distribution whether water is piped or carried into the home. Many communities have protected or improved water supplies and treated water that is microbiologically safe when collected or when it leaves a treatment plant. However, substandard water distribution systems, intermittent water pressure due to power outages and other disruptions, and illegal connections to the distribution system often lead to the introduction of fecal contamination and therefore, microbiologically contaminated water at the consumer's tap or collection point. In some urban water supplies the infrastructure for water distribution to consumers is so inadequate that pressure drops, losses and other intermittent pressure changes, deteriorating, open or leaking conveyances and other distribution system deficiencies lead to infiltration or intrusion of contaminated water and increased waterborne disease risks. Such deficiencies result in the delivery of unsafe water to consumers, even though the water may have been obtained from a high quality, protected source and centrally treated by physical and chemical methods to improve quality. Furthermore, 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. Because these unserved urban dwellers are forced to obtain water from any available source, including informal and clandestine connections to the central water supply system, their water is typically contaminated.

People now drinking unsafe household water also include those in rural as well as urban settings. Many rural dwellers lack indoor plumbing or nearby outdoor piped water from a safe supply (from wells, boreholes, protected or upland surface water sources, etc.). Often they have to travel considerable distances to reach any water source, regardless of quality, for collection and household use (White et. al., 1972). Many urban dwellers are also lack safe water (WHO, 2000; Swerdlow et. al., 1992; Ries et. al., 1992; Weber et. al., 1994).

A further problem is that water collected for domestic use often becomes re-contaminated or further contaminated by unsafe consumer storage and handling practices at the household level. Many of the world's people continue to obtain their water on a daily or other frequent basis from any available source and either carry it or otherwise have it delivered to the home for personal use. Typically, this water is gathered and stored in vessels of various designs and materials. Often, the water is not treated or otherwise protected from subsequent contamination during use. Such household water is at high risk of being contaminated by various pathogenic viruses, bacteria and parasites associated with fecal wastes and other sources. This is because water is typically obtained from the most convenient source, which is often fecally contaminated, and typically, additional contamination occurs due to a variety of unsanitary conditions and practices during storage and use. Microbial contamination of collected and stored household water is caused not only by the collection and use of fecally contaminated water that was not safe to begin with but also by contamination of initially microbiologically safe water after its collection and storage. Factors contributing to this problem are unsanitary and inadequately protected (open, uncovered or poorly covered) water collection and storage containers, the use of unsanitary methods to dispense water from household storage vessels, including fecally contaminated hands and dippers, lack of protection against contamination introduced by vectors (flies, cockroaches, rodents, etc.) and inadequate cleaning of vessels to prevent biofilm formation and accumulation of sediments and pathogens.

Improving and protecting the microbial quality and reducing the infectious disease risks to consumers of collected water stored in households requires alternative or interim strategies and approaches that can be implemented effectively, quickly and affordably. As will be described in this report, technically feasible, effective, socioculturally acceptable and affordable methods for treatment and storage of household water to improve microbial quality and reduce waterborne disease risks are now available. Waiting for the provision of piped, microbiologically safe community water systems to the many people lacking such services is an inappropriate response to the basic need for safer drinking water that can be met on at least a provisional basis by available technologies. Effective measures are needed immediately to provide at risk populations with safer water at the household level until the long-term goal of providing safe, piped, community water supplies can be achieved.

There is now conclusive evidence that simple, acceptable, low-cost interventions at the household and community level are capable of dramatically improving the
microbial quality of household stored water and reducing the risks of diarrheal disease and death in populations of all ages in the developed and developing world. A variety of physical and chemical treatment methods to improve the microbial quality of water are available and many have been tested and implemented to varying extents in a variety of settings and for a diverse range of populations. Many different water collection and storage systems and strategies have been developed, described and evaluated on the basis of various criteria for household and community use. Some of them have been tested under controlled conditions in the laboratory and implemented in field to evaluate their ability to produce drinking water of acceptable microbiological quality and to maintain this quality during storage and use. Some of them also have been evaluated in the field for their ability to reduce diarrheal and other waterborne diseases among users. Because of the importance of education, socio-cultural acceptance, changing people's beliefs and behaviors, achieving sustainability and affordability in the provision of safe water, some of the most promising household water treatment and storage systems and their implementation strategies include or are accompanied by efforts to address these considerations.

The purpose of this report is to critically review the various candidate technologies and systems for providing microbiologically improved household water and to identify the most promising ones based on their technical characteristics and performance criteria. These characteristics and performance criteria are: effectiveness in improving and maintaining microbial water quality, reducing waterborne infectious disease, technical difficulty or simplicity, accessibility, cost, socio-cultural acceptability, sustainability and potential for dissemination. The focus of this critical review is on technologies and systems to protect water during storage collection and use, improve the microbial quality of the collected water, and thereby reduce pathogen exposure and risks of diarrheal and other waterborne diseases. This is not intended to be a comprehensive review of water treatment methods that reduce and thereby minimize exposures to various chemical contaminants. While toxic chemicals in drinking water are an important public health concern, it has been repeatedly demonstrated and generally accepted that the most important and immediate risks to human health by using contaminated drinking water are those from enteric microbes of fecal origin or other sources. Hence, the focus herein is on strategies and systems for protection and improvement of the microbiological quality of household water and prevention and control of waterborne microbial diseases. However, some of the technologies that reduce waterborne microbes also reduce certain toxic chemicals, such as arsenic.

1.2. Purposes and Benefits of Household Water Treatment and Storage

The purposes of household water treatment and storage addressed in this review are those intended to improve and maintain the microbial quality of the water for drinking and other potable purposes, such as food preparation and essential hygiene in child care and treatment of illness (breast feeding and preparation of infant foods and oral rehydration solutions) and thereby reduce disease transmission. The main benefit of microbiologically safe water for these purposes should be obvious: reducing the risks of diarrheal and other waterborne infectious diseases. The alternative, unsafe water, is a major source of pathogen exposure and increased risk of waterborne infection, illness and death. Hence, the provision of microbiologically safe household water has the potential to reduce the infectious burden of the developing world's population.
Recent estimates put this burden at 4 billion cases of diarrhea and 2.2 million deaths annually, mostly in children under five years of age. A compelling reason to accept and promote treatment and safe storage of collected household water to improve microbial quality is the ability of this health-related intervention to reduce the infectious disease burden of the user population. Notably, it is now well documented that the provision of safe water alone will reduce diarrheal and other enteric diseases by 6 to 50%, even in the absence of improved sanitation or other hygiene measures. Reducing household diarrheal disease by more than 5% is an important achievement, because this is the minimum achievable target reduction in disease burden considered worthy of promotion and implementation by health authorities. Furthermore, as will be documented later in this report, reductions in diarrheal disease burdens in excess of 5% by household water treatment and safe storage have been achieved for children under 5 years of age. This outcome clearly shows that children under age 5 are protected by the intervention of household treatment and safe storage of collected water, despite the likely opportunities for transmission of these diarrheal disease agents by other exposure routes. Hence, treating water at the household level and storing it safely to improve microbial quality apparently reduces the frequency and magnitude of encounters of children under age 5 with diarrheal pathogens in the home.

Although the combined roles of safe water and adequate hygiene and sanitation in reducing diarrheal and other diseases are clear and well documented, there is uncertainty and even debate over the magnitude of the contribution of safe water to this outcome (Esrey et al., 1985; 1991). Some studies have suggested that improved hygiene and sanitation are more important than safe water in reducing diarrheal and other water-borne and water-washed diseases (US Agency for International Development, 1993). In the minds of some, the provision of safe water alone is unlikely to result in reductions of diarrheal and other infectious diseases. This is because the other transmission routes of these potentially waterborne diseases, such as person-to-person contact, food, fomites and vectors are not being controlled and continue to be major sources of pathogen transmission. Hence, it is assumed that provision of microbiologically safe water alone will have little or no beneficial effect on infectious disease transmission in the absence of improved sanitation and other hygiene measures. This assumption is now known to be incorrect. Recent studies of only safe water interventions clearly document not only the improved microbiological quality of household water but also significant reductions in diarrheal disease (Handzel, 1998; Mintz et. al., 2001; Quick, 1997; Quick et. al., 1999; Semenza et. al., 1998). This beneficial effect is especially achieved when the technological intervention for improved household water treatment and storage is supported by educational and motivational efforts to transfer the technology and develop individual and community understanding and support to maintain compliance and assume responsibility for its continued use and dissemination. It is also clear that the combined roles of safe water and adequate hygiene and sanitation are likely to achieve the greatest reduction in infectious disease burden compared to either intervention alone. However, it is now apparent that improving household water collection, treatment and storage is one option for achieving a beneficial health effect by reducing diarrheal and other infectious diseases. Household water treatment and storage systems are one of many water, sanitation and hygiene options that deserve due consideration in the identification, prioritization and implementation of water, sanitation and hygiene measures for use at household, community and regional levels.
It is assumed that treated community water supplies in developed countries generally are of high microbiological quality and therefore safe with respect to waterborne microbial disease risks. However, significantly increased risks of waterborne gastrointestinal illness have been attributed to a centralized community water supply system in a large city of a developed country (Laval, Quebec, Canada) where water was extensively treated by modern methods and met all microbial quality requirements (Payment et al, 1991; 1996). These findings suggest that pathogens at levels below detection but high enough to cause measurable gastrointestinal illness either penetrated the multiple treatment barriers or they entered the treated water subsequently in the community distribution system or within household plumbing. Hence, even extensively treated community drinking water of high microbiological quality and assumed to be of low risk in developed countries may still be contributing significantly to community diarrheal illness. It is noteworthy that the apparent risks of waterborne diarrheal illness from the treated community water delivered by the distribution system were significantly decreased either by point-of-use water treatment or by protecting the treated water from post-treatment contamination (i.e., bottling it at the treatment plant and delivering the bottles to consumers). Additionally, the infectious disease risks from fecally contaminated and microbiologically unsafe water in developed countries is considered even greater in the water supplies of smaller communities than the larger ones. Small community water supplies are at greater risk than larger ones because they often lack the technical expertise and financial resources to adequately protect source waters, provide sufficient and technically reliable treatment and maintain the integrity of their distribution systems. For example, most waterborne outbreaks in the United States of America are due to systems with no or inadequate treatment, vulnerable watersheds and aquifers, distribution system deficiencies and serving smaller communities. Therefore, it should come as no surprise that in communities throughout the world, improving household water quality by point-of-use treatment reduces risks of diarrheal disease and significantly improves microbial quality.

In this review the candidate technologies and approaches for household water treatment and storage are examined on the basis of their technical feasibility, practicality and availability, effectiveness in improving the microbiological quality of the water and reducing waterborne disease, cost, and potential for sustainability and dissemination.

2. Storage and Treatment of Household Water

2.1. Household Water Storage, Microbial Quality and Infectious Disease Risks
Key factors in the provision of safe household water include the conditions and practices of water collection and storage and the choice of water collection and storage containers or vessels. As shown in Table 1, numerous studies have documented inadequate storage conditions and vulnerable water storage containers as factors contributing to increased microbial contamination and decreased microbial quality compared to either source waters or water stored in improved vessels. Some studies also have documented increased risks of waterborne infectious diseases from inadequately stored water compared to water stored in an improved vessel (safe storage), treated in the home to improve microbial quality, or consumed from a quality source without storage (Table 1). Higher levels of microbial contamination