year or two), the need for a reliable source of electricity to power the lamps, the need for period cleaning of the lamp sleeve surface to remove deposits and maintain UV transmission, especially for the submerged lamps, and the uncertainty of the magnitude of UV dose delivered to the water, unless a UV sensor is used to monitor the process. In addition, UV provides no residual chemical disinfectant in the water to protect against post-treatment contamination, and therefore care must be taken to protect UV-disinfected water from post-treatment contamination, including bacterial regrowth or reactivation.

3.9 Costs of UV disinfection for household water

Because the energy requirements are relatively low (several tens of watts per unit or about the same as an incandescent lamp), UV disinfection units for water treatment can be powered at relatively low cost using solar panels, wind power generators as well as conventional energy sources. The energy costs of UV disinfection are considerably less than the costs of disinfecting water by boiling it with fuels such as wood or charcoal.

UV units to treat small batches (1 to several liters) or low flows (1 to several liters per minute) of water at the community level are estimated to have costs of 0.02 US$ per 1000 liters of water, including the cost of electricity and consumables and the annualized capital cost of the unit. On this basis, the annual costs of community UV treatment would be less than US$1.00 per household. However, if UV lamp disinfection units were used at the household level, and therefore by far fewer people per unit, annual costs would be considerably higher, probably in the range of $US10-100 per year. Despite the higher costs, UV irradiation with lamps is considered a feasible technology for household water treatment.

4. Physical removal processes: sedimentation and filtration

4.1 Microbe size and physical removal from water

Microbes and other colloidal particles can be physically removed from water by various processes. The sizes of the microbes are especially important for their removal by sedimentation and filtration. Viruses are the smallest waterborne microbes (20 to about 100 nanometers in size) and the most difficult to remove by filtration and other size exclusion methods. Bacteria are somewhat larger than viruses (about 0.5 to 3 micrometers) but too small to be readily removed by plain sedimentation or settling. Protozoan parasites are the next largest in size (most are about 3 to 30 micrometers) and only the largest ones are likely to gravity settle at appreciable rates. Protozoan removal efficiency by filtration varies with parasite size and the effective pore size of the filter medium. Helminths are multicellular animals, but some are important waterborne pathogens because their eggs (ova) and waterborne larval stages can be waterborne. Most helminths of concern in water are large enough to gravity settle at appreciable rates; they are readily removable by settling and various filtration processes.

Although viruses, bacteria and the smaller protozoans are too small to gravity settle, these waterborne pathogens are often associated with larger particles or they are aggregated (clumped). Aggregated or particle-associated microbes are easier to remove by physical processes than the free or dispersed microbes. Consequently, observed reductions of waterborne microbes by physical removal processes are sometimes greater than expected or anticipated based strictly on their individual sizes. In some situations, efforts are made to promote the association of pathogens with larger particles, such as by coagulation-flocculation, to promote their physical removal. Such methods will be described in later sections of this report.

4.2 Plain sedimentation or settling

The microbial quality of water sometimes can be improved by holding or storing it undisturbed and without mixing long enough for larger particles to settle out or sediment by gravity. The settled water can then be carefully removed and recovered by decanting, ladling or other gentle methods that do not disturb the sedimented particles. Sedimentation has been practiced since ancient times using small water storage vessels or larger settling basins, reservoirs and storage tanks. The advantages and disadvantages of plain sedimentation for household treatment of water are summarized in Table 8.

Table 8. Advantages and Disadvantages of Plain Sedimentation for Household Water Treatment

Advantages	Disadvantages	Comments
Simple, low cost technology to reduce settable solids and perhaps some microbes for water	Only settable solids, such as sands, silts and larger microbes settle efficiently; clays and smaller microbes do not settle; only moderate to low microbe reductions	Can be applied to large and small volumes of water using commonly available water collection and storage vessels; settled material must be removed and vessels cleaned regularly
Removal of settable solids can reduce turbidities and make the water more amenable to other treatment methods to reduce microbes	In some waters solids are not efficiently removed by settling and alternative methods of removing solids are required	Reduced levels of solids (turbidity) improves penetration of UV radiation (from sunlight), decreases oxidant (e.g., chlorine) demand, decreases solids-associated pathogens
Recommended as a simple pre-treatment of household water prior to application of other treatments to reduce microbes	Unreliable method to reduce pathogens; solids are not efficiently removed by settling from some waters; can be labor-intensive	Pre-treatment to remove solids (turbidity) is recommended for turbid waters prior to solar or chemical disinfection

Storing water for as little as a few hours will sediment the large, dense particles, such as inorganic sands and silts, large microbes and any other microbes associated with larger, denser particles. However, clay particles and smaller microbes not associated with large or dense particles will not settle under these conditions. Longer settling times, such as overnight or for 1-2 days, will remove larger microbes, including helminth ova and some parasites, some nuisance microbes, such as certain algae, and the larger clay particles. Most viruses and bacteria and fine clay particles are too small to be settled out by simple gravity sedimentation. Therefore, microbial reductions by plain sedimentation or gravity settling are often low and inconsistent. Overall reductions of viruses and bacteria by sedimentation rarely exceed 90%, but reductions of helminth ova and some protozoans can exceed 90%, especially with longer storage times of 1-2 days.

Sedimentation of household water can be done in simple storage vessels, such as pots and buckets. Care must be taken to avoid disturbing the sedimented particles when recovering the supernatant water by decanting or other methods. Typically, at least two containers are needed to settle water: one to act as the settling vessel and another to be the recipient of the supernatant water after the settling period. Water also can be settled in larger bulk storage systems, such as cisterns, basins and tanks. Regardless of the sedimentation vessel, it is essential that solids are removed and the vessel cleaned on a regular basis. When water is sedimented in small collection or storage vessels, the sediment should be removed and the vessel cleaned after each use. At minimum, cleaning should be by rinsing with freshly collected source water. More rigorous physical or chemical cleaning is recommended to avoid the microbial colonization of the vessel surfaces and the resulting accumulation of a biofilm. For sedimentation in larger, stationary vessels and basins, such as cisterns and sedimentation tanks (some of which are designed to collect and store water for individual or small groups of households), protection of the water during storage, sanitary collection of the supernatant water after settling, and systems and procedures to clean the storage vessel also are critical

Sedimentation often is effective in reducing water turbidity, but it is not consistently effective in reducing microbial contamination. However, turbidity reductions often improve microbial reductions by physical and chemical disinfection processes, such as solar treatment and chlorination, respectively. Hence, plain sedimentation or gravity settling of highly turbid water for household use is recommended as a pre-treatment for systems that disinfect water with solar radiation, chlorine or other chemical disinfectants. Furthermore, sedimentation of particles improves the aesthetic qualities of the water and thereby increases its acceptance by consumers. Pre-treatment of turbid household water by sedimentation is recommended because is easy to perform and requires a minimum of materials or skill. It can be done with as little as two or more vessels by manually transferring (e.g., pouring and decanting) the water. For turbid waters containing non-settable solids, sedimentation will be ineffective and alternative methods of particle removal, such a filtration, are needed.

4.3 Filtration

Filtration is another ancient and widely used technology that removes particles and at least some microbes from water. As shown in Table 9, a variety of filter media and filtration processes are available for household or point-of-use treatment of water. The practicality, ease of use, availability, accessibility and affordability of these filtration media and methods vary widely and often depend on local factors. The effectiveness of these filtration methods in reducing microbes also varies widely, depending on the type of microbe and the type and quality of the filtration medium or system

Table 9. Filters and Filtration Media for Treatment of Household Water: Characteristics, Advantages and Disadvantage

Type Of Filtration	Media	Avail-ability	Ease of Use	Effectiveness (comments)	Cost
Granular media, rapid rate depth filter	Sand, gravel, diatomaceous earth, coal, other minerals	High	Easy to Moderate	Moderate* (depends on microbe size and pre-treatment)	Low to moderate
Slow sand filter	Sand	High	Easy to moderate (community use)	High** in principle but often low in practice	Low to moderate
Vegetable and animal derived depth filters	Coal, sponge, charcoal, cotton, etc.	Medium to high	Moderate to Difficult	Moderate*	Low to moderate
Fabric, paper, membrane, canvas, etc. filter	Cloth, other woven fabric, synthetic polymers, wick siphons	Varies: some low; others high	Easy to moderate	Varies from high to low (with pore size and composition)	Varies: low for natural; high for synthetics
Ceramic and other porous cast filters	Clay, other minerals	Varies: high- low, with materials availability and fabrica-tion skill	Moderate. Must be physically cleaned on a regular basis to prevent clogging and biofilm growth	Varies from high to low (with pore size and ceramic filter quality)	Moderate to high
Septum and body feed filters	Diatomaceous earth, other fine media	Varies	Moderate to difficult; dry media a respiratory hazard	Moderate	Varies

* Moderate typically means 90-99% reductions of larger pathogens (helminth ova and larger protozoans) and solids-associated pathogens, but low (<90%) reductions of viruses and free bacteria, assuming no pre-treatment. With pre-treatment (typically coagulation), pathogen reductions are typically >99% (high).
**High pathogen reduction means >99%.

4.4 Granular media, rapid rate filters and filter media

Filtration through porous granular media, typically sand or successive layers of anthracite coal and sand, is the most widely used physical method for water treatment at the community level, and it has been used extensively for on-site treatment of both community and household water since ancient times (Oza and Chaudhuri, 1975; Chaudhuri and Sattar, 1990; Logsdon, 1990; LeChevallier and Au, 2002). A number of different granular media filters for household and other small-scale uses have been described, including so-called bucket filters, drum or barrel filters, roughing filters in the form of one or more basins, and above or below grade cistern filters. Granular media used for water filtration include sand, anthracite, crushed sandstone or other soft rock and charcoal. In recent years, efforts have been made to improve the performance of granular filter media for removing microbial contaminants by coating or co-mingling sand, coal and other common negatively charged granular media with metal oxides and hydroxides of iron, aluminum, calcium or magnesium (Chaudhuri and Sattar, 1990; Chaudhuri and Sattar, 1986; Prasad and Chaudhuri, 1989). Such modified media are positively charged and therefore, more effective for removing and retaining the negatively charged viruses and bacteria by electrostatic adsorption (Chaudhuri and Sattar, 1986). Some improved granular media filter-adsorbers have incorporated bacteriostatic agents, such as silver, in order to prevent the development of undesirable biofilms that release excessive levels of bacteria into the product water (Ahammed and Chaudhuri, 1999). The production of these more advanced filter media containing charge-modified materials and bacteriostatic agents requires specialized skills and facilities, which are beyond the capabilities of most household users. Such media would have to be prepared and distributed to communities and households from specialized facilities. However, naturally occurring, positively charged granular media, such as naturally occurring iron oxide-coated sands or deposits of iron, aluminum, calcium or magnesium minerals, may be no more difficult or costly to obtain and prepare for household water filtration than otherwise similar negatively charged granular media.

A number of different designs and scales (sizes) of rapid, granular media filters are available for household and community water treatment. For household use bucket filters, barrel filters and small roughing filters are the main choices. The advantages and disadvantages of these filter designs are summarized in Table 10.

Table 10. Advantages and Disadvantages of Different Granular Medium Filters for Household Use

Filter Design or Type	Advantages	Disadvantages
Bucket filter	Useable on a small scale at household level; simple; can use local, low cost media and buckets; simple to operate manually; low (<90%) to moderate (90-99%) turbidity reduction	May require fabrication by user; initial education and training in fabrication and use needed; requires user maintenance and operation (labor and time). Commercial ones are relatively expensive. Low (<90%) pathogen reduction.
Barrel or drum filter	Useable on a small scale at household or community level; relatively simple; can use local, low cost media and barrels or drums; relatively easy to operate manually; low to moderate turbidity reduction.	Requires some technical know-how for fabrication and use; initial education and training needed; requires user maintenance and operation (some skill, labor and time). Low (<90%) pathogen reduction.
Roughing filter	Useable on a small scale at community level; relatively simple; can use local, low cost construction material and media; relatively easy to operate manually; low to moderate turbidity reduction	Less amenable to individual household use because of scale; requires some technical know-how for construction and use; initial education and training needed; requires user maintenance and operation (skill, labor and time). Low (<90%) pathogen reductions

4.4.1 Bucket filters

Bucket filter systems of granular media for household use usually require two or three buckets, one of which has a perforated bottom to serve as the filter vessel. The bucket with the perforated bottom is filled with a layer of sand, layers of both sand and gravel, or other media. Gravel and sand media of specified sizes often can be purchased locally. Alternatively, these media can be prepared locally by passing sand and gravel through metal sieves of decreasing mesh size and retaining the material in the appropriate size ranges (between 0.1 and 1 mm for sand and about 1-10 mm for gravel). Sand or other local granular media are placed in plastic or metal buckets approximately 2.5-gallon (10-liter) to 10-gallon (40-liter) capacity and having bottoms with perforations (punched with small holes and fitted with a mesh strainer, such as window screen or piece of cloth) to allow water to drain out. Buckets are filled with several cm of gravel on the bottom and then a deeper layer of sand (about 40 to 75 cm) on top of the gravel. The granular medium bucket filter is suspended above a similar size empty bucket with a solid bottom to collect the water that drains from the filter as water is poured through it. The media of newly prepared bucket filters, as well as that of larger drum and roughing filters, must be cleaned initially with water to remove fine material and other impurities. So, the dirty water draining from new filters is discarded until the filtrate water has a low turbidity. The media of bucket filters must be cleaned or replaced on a regular basis to remove accumulated particles and to prevent the development of excessive microbial growths that will degrade water quality. The frequency of filter media replacement and cleaning depends on local conditions, but typically it is after a use period of perhaps several weeks.

A number of commercial sources of bucket filters are available and some have been used in both developing countries for small community and household water treatment. On of the better known and more widely distributed of these is the so-called commercial, two-bucket, point-of- use, media filter system. It consists of two 5-gallon plastic buckets with lids, filters and accompanying assembly fittings and contains both a particulate and a carbon filter. It is recommended that water be chlorinated before filtration. Use of chlorination adds complexity to the operation of the filter system and make its use more difficult, less practical and more costly, especially for the developing world. The system sells for about $US 50.00 and is designed to provide drinking water for up to 10 people per day. Replacement filter units are about $US 20.00 plus shipping. These costs are beyond the means of the world's poorest people in developing countries. However, the commercial, two-bucket, point-of-use, media filter system has been subsidized and distributed in developing countries by NGOs and is used in small communities, primarily in disaster relief settings.

4.4.2 Drum or barrel filters

A number of different designs for drum or barrel filters having either up-flow or down-flow of water have been described for use as rapid granular medium filters. These filters are usually 55-gallon (about 200-liter) capacity steel drums and contain sand and gravel media similar to that used for bucket filters (Cairncross and Feachem, 1986; IDRC, 1980; Schiller and Droste, 1982). The filters generally have a cover to prevent the introduction of airborne and other contaminants. Down-flow filters have a perforated pipe at the bottom to collect the water passing through the medium and discharge it from the side of the drum. The outlet pipe for filtered water may discharge the water at the bottom of the drum or it may be configured with an upward bend or loop to discharge the water at the same level as the top of the media in the filter. Upward flow filters have a bottom inlet and a rigid perforated or porous plate to support the filter media, which is usually coarse sand. Water flows in an upward direction and discharged through a side opening near the top of the drum. As with other granular media filters, the media of drum filters must be cleaned initially and on a regular basis. Cleaning down-flow filters tends to be technically more difficult and inconvenient. Water either has to be forced through the filter media in an up-flow direction in place, so-called backwashing, and the backwash water discarded, or the media has to be physically removed and replaced with cleaned or fresh media. Stopping the upward flow of product water and opening a bottom drain plug to discharge down-flowing dirty water that passes through the filter medium more easily cleans up-flow filters. An upward flow granular medium filter consisting of two tanks in a vertical series, with the lower tank containing a layer of charcoal sandwiched between two layers of fine sand and the upper tank the collector of the filtrate has been designed by UNICEF to treat 40 L of water per day (Childers and Claasen, 1987). The extent to which this filter reduces microbial contaminants in water has not been reported. However, if it is anticipated these filters function as typical rapid granular media filters, pathogen reductions are likely to be no more than 90% and even less (~50%) for the smallest pathogens, the enteric viruses.

4.4.3 Roughing filters

Simple, low cost, low-maintenance, multi-stage roughing filters for household and community use have been described and characterized (Galvis et al., 2000; Wegelin and Schertenlieb, 1987; Wegelin et al., 1991). Typically, these filters are rectangular, multi-compartment basins constructed of concrete or other materials. They require modest skills for operation and maintenance, and therefore, are best suited for use by communities or at least multiple households. However, it is possible for these multi-compartment tanks to be centrally fabricated and distributed at low cost for placement and final installation at their locations of use. Many of these filters are designed to use two different sizes of low cost, coarse granular media in two or three compartments or stages, and such media are generally locally available. In a typical, design water flows horizontally (or vertically in either an upflow or downflow mode) into an initial chamber containing fine gravel or coarse sand and then into another chamber or (two successive chambers) containing coarse or medium sand having smaller particle sizes than the initial chambers and from which is then discharged as product water. For highly turbid water containing settleable solids, a horizontal or vertical sedimentation basin to remove this coarse material prior to filtration precedes the filter. The filter has provision for backwashing the medium from a valved inlet (at the bottom of the filter medium chamber in the horizontal and downflow filter designs). Roughing filters usually consist of differently sized filter material decreasing successively in size in the direction of flow. Most of the solids are separated by the coarse filter medium near the filter inlet, with additional removal by the subsequent medium and fine granular media in subsequent compartments. Roughing filters are operated at relatively low hydraulic loads or flow rates. Regular backwashing is required to main flow rates and achieve efficient particulate removals, and therefore, some skill and knowledge is required to properly operate and maintain a roughing filter. Removal of indicator bacteria by roughing filters has been reported to be 90-99%. Although not reported, it is expected that compared to bacteria removals, virus removals would be lower and parasite removals would be similar to or higher.

4.4.4 Filter-cisterns

Filter-cisterns have been in use since ancient times in areas heavily supplied with rainwater or other water sources but lacking land area for reservoir or basin storage (Baker, 1948). In this filtration system cisterns or large diameter well casings, partially below grade, are surrounded by sand filters, such that water flows through the sand and into the casing or cistern either from the bottom or though side of the casing near the bottom. Such filter-cisterns function as infiltration basins to remove turbidity and other particulates. Among the best known of these filter-cistern systems were those of the city of Venice, which date back at least several hundred years (to the mid-15th century). The sand filter rings were several meters deep and in the shape of an inverted cone or pyramid in the center of, which was a cylindrical cistern or well casing that, collected the filtered water. The Venetian filter-cisterns were recognized for their ability to provide "clear and pure" water free "bad qualities". Today, filter-cisterns are being used in Sri Lanka to treat and store rainwater from roof catchment systems (Stockholm Water Symposium, 2000).

4.4.5 Biomass and fossil fuel granular media filters

Historically, depth filters composed of filter media derived from vegetable and animal matter have been employed for water treatment. Coal-based and charcoal filter media have been used since ancient times and carbon filter media are widely used today for both point-of-use and community water filtration systems (Argawal and Kimondo, 1981; Baker, 1948; Chaudhuri and Sattar, 1990). Filters containing sponges were widely used for on-site or point-of-use household and military water treatment in 18th century France. Water vessels had holes in their sides into which sponges were pressed, and water was filtered as it passed through the compressed sponges. Other filter designs consisted of sponges compressed into a perforated plate through which water was poured. Sponge filters imparted objectionable tastes and odors to the water unless they were cleaned regularly, indicating that microbial growths and biofilms probably were a major problem with these filters. Other media also employed in these point-of-use filters included sand, cotton, wool, linen, charcoal and pulverized glass, either individually or in various combinations as successive layers. These media also were used in larger scale filters for community water supply. Other examples of vegetable matter depth filters are those containing burnt rice hulls (as ash) or those consisting of vessels or chambers containing fresh coconut fibers and burnt rice husks in series (Argawal and Kimondo, 1981; Barnes and Mampitiyarachichi, 1983).

4.4.6 Microbial reductions by rapid granular media filters and recommended uses

Rapid granular media filters of the types described above are capable of reducing turbidities and enteric bacteria by as much as 90% and reducing larger parasites such as helminth ova by >99%. Because of their small size (typically <0.1 micrometer), enteric viruses are not appreciably removed by rapid granular media, with typical removals of only 50%-90%. These filters remove only viruses associated with other, larger particles or aggregated in larger particles. When roughing filters have been applied to highly turbid surface waters, removals have ranged from about 50 to 85% for bacteria and yeast's, with microbial removal efficiency depending on the type of filter medium (El-Taweel and Ali, 2000). The reduction of viruses and bacteria in rapid granular medium filters can be greatly increased (to >99%) if the filter medium is positively charged. This is accomplished by combining granular media such as coal (lignite, anthracite, etc.) with positively charged salts, such as alum, iron, lime or manganese. In positively charged filter media virus and bacteria reductions of 90->99% have been reported (Gupta and Chaudhuri, 1995; Chaudhuri and Sattar, 1990; Chaudhuri and Sattar, 1986; Prasad and Malay, 1989). Coal treated with alum or a combination of alum and silver was most effective for microbial reductions. Vegetable matter filters, such as those composed of burnt rice hull ash, have been reported to dramatically reduce turbidity, reduce bacteria by about 90% and require media replacement only every 2-4 months in southeast Asia (Argawal et al., 1981). Rice hull ash filters operated at a flow rate of 1 $m^3/m^2/hr$ reduced *E. coli* by 90 to 99%, which was higher than the *E. coli* removal by a sand filter tested under similar conditions (Barnes and Mampitiyarachichi, 1983). However, such vegetable matter filters, as well as many of the other designs of low cost granular media filters, have not been adequately evaluated for their ability to reduce a wide range of enteric pathogens, including enteric viruses, or their susceptibility to microbial growths and biofilms that can degrade the quality of the filtered water. Technological methods to modify granular media, such as chemical modification to impart positive surface charges, can improve microbial removals by filtration. However, such modifications are to technically demanding to be applied at the household level and therefore, are recommended primarily for piped community water supply systems.

Overall, simple granular media filters, including bucket, barrel or drum and roughing filters, are appropriate technologies for water treatment in at the community and perhaps the household level. They are effective in reducing turbidity but achieve only low to moderate microbe reductions, unless modified to make the media positively charged. Of these filter designs, the bucket filter is probably the most appropriate for household use because of its small scale, simplicity and manual application to quantities of water collected and used by individual households. Barrel or drum filters and roughing filters are more appropriate for community use or for sharing among several households within a community. However, none of these filtration methods achieve consistently high reductions of pathogens, unless chemically modified filter media are employed or the filtration process is combined with chemical disinfection such as chlorination. Therefore, granular media filters are best used at pre-treatment processes to reduce turbidity and provide product water that is more amenable to pathogen reductions by disinfection processes, such as solar radiation or chlorination. Due to their variable and potentially low microbe reductions, typical granular medium filters (not containing chemically modified media) are not recommended a standalone treatment for household water supplies.

4.5 Slow sand filters

Slow sand filtration of drinking water has been practiced since the early 19th century and various scales of slow sand filters have been widely used to treat water at the community and sometimes local or household level (Cairncross and Feachem, 1986; Chaudhuri and Sattar, 1990; Droste and McJunken, 1982; Logsdon, 1990). Most are designed as either barrel filters, basins or galleries containing a bed of about 1-1.25 meter of medium sand (0.2 to 0.5mm) supported by a gravel layer incorporating an underdrain system. The filters operate with a constant head of overlying water and a flow rate of about 0.1 m/hour. Slow sand filtration is a biological process whereby particulate and microbial removal occurs due the slime layer ("schmutzdecke") that develops within the top few centimeters of sand. Reductions of enteric pathogens and microbial indicators are relatively efficient and generally in the range of 99% or more, depending on the type of microbe. Therefore, microbial reductions by slow sand filtration can be high, if the filters are properly constructed, operated and maintained. However, slow sand filters often do not achieve high microbial removals in practice, especially when used at the household level. This is because of inadequacies in constriction, operation and maintenance and the lack of institutional support for these activities.

Because of the development of the schmutzdecke and its accumulation of particles removed from treated water, the top layer (5-10 cm) of sand must be manually removed and replaced on a regular but usually infrequent basis. The removed sand is generally cleaned hydraulically for later reuse. Labor to clean larger scale community sand filters has been estimated at 1 to 5 hours per 100 m^2 of filter surface area. Freshly serviced slow sand filters require time for reestablishment of the schmutzdecke or "ripening" to achieve optimum performance, and therefore, multiple filter units are recommended. The performance and operation cycles of slow sand filters is influenced by raw water quality. Highly turbid waters are difficult to filter directly and may require a pre-treatment procedure, such as sedimentation or roughing filtration, to reduce turbidity. Slow sand filters are an appropriate, simple and low cost technology for community water treatment in developing countries. However, they are not recommended for individual household use because of their relatively large size (surface area), and the needs for proper construction and operation, including regular maintenance (especially sand scraping, replacement and cleaning) by trained individuals. Such demands for achieving good performance are unrealistic because they are beyond the capacities and capabilities of most households.

4.6 Fiber, fabric and membrane filters

Filters composed of compressed or cast fibers (e.g., cellulose paper), spun threads (cotton) or woven fabrics (cotton, linen and other cloths) have been used to filter water and other beverages (e.g., wine) since ancient times. The use of wick siphons made of wool thread and perhaps other yarns to filter water was well known in the days of Socrates and Plato (about 350 to 425 BCE) (Baker, 1948). Various compositions, grades and configurations of natural fiber and synthetic polymer filter media materials continue to be widely used today for point-of-use and small community water supply systems. In their simplest applications these filters are simply placed over the opening of a water vessel through which particulate-laden water is poured. Another simple application is to place a cone shaped filter in a funnel through which water is poured and collected in a receiver vessel. The particles are removed and collected on the filter media as the water is poured into the vessel. Other paper and fibrous media filters are in the form of porous cartridges or thimbles through which water is poured to exit from the bottom, or alternatively, which are partially submerged in are water so that filtered water passes to the inside and accumulates within. More advanced applications employ filter holders in the form of porous plates and other supports to retain the filter medium as water flows through it.

Paper and other fibrous filter media retain waterborne particles, including microbes, by straining them out based on size exclusion, sedimenting them within the depth of the filter matrix or by adsorbing them to the filter medium surface. Therefore, removal is dependent on the size, shape and surface chemistry of the particle relative to the effective pore size, depth and surface physical-chemical properties of the filter medium. Most fabric (cloth) and paper filters have pore sizes greater than the diameters of viruses and bacteria, so removal of these microbes is low, unless the microbes are associated with larger particles. However, some membrane and fiber filters have pore sizes small enough to efficiently remove parasites (one to several micrometers pore size), bacteria (0.1-1 micrometer pore size) and viruses (0.01 to 0.001 micrometer pore size or ultrafilters). Typically, such filters require advanced fabrication methods, special filter holders and the use of pressure to force the water through the filter media. For these reasons, such filters and their associated hardware are not readily available and their costs generally are too high for widespread use to treat household water in many regions and countries. However, simple fiber, fabric, paper and other filters and filter holders for them are available for widespread, practical and affordable household treatment of collected and stored water throughout much of the world.

Some waterborne and water-associated pathogens are relatively large, such as the 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 zooplankters in water, such as the bacterium *Vibrio cholerae*. Various types of filters, including fabric and paper filters can physically remove these larger, free-living pathogens as well as the smaller ones associated with larger planktonic organisms. Paper filters have been recommended for the removal of schistosomes and polyester or monofilament nylon cloth filters have been recommended for the removal of the *Cyclops* vector of guinea worm (Imtiaz et al., 1990). Such filters have been used successfully at both the household and community levels (Aikhomu et al., 2000). Colwell and colleagues have shown that various types of sari cloth (fine mesh, woven cotton fabric) and nylon mesh can be used in single or multiple layers to remove from water the zooplankton and phytoplankton harboring *V. cholerae*, thereby reducing the *V. cholerae* concentrations by >95 to >99% (Huq et al., 1996). Where waterborne schistosomes, guinea worms, *Faciola* species and zooplanton-associated *V. cholerae* are a problem, use of these simple, point-of-use filter methods are recommended and encouraged, especially if other control measures are not available or difficult to implement.
However, typical fabric, paper, monofilament nylon and similar filters are not recommended for general treatment of household water. This is because the pore sizes of these filters are too large to appreciably retain viruses, bacteria and smaller protozoan parasites, especially if such microbes are free and not associated with large particles or organisms. Therefore, other types of physical or chemical water treatment processes are usually needed to effectively control a wider range of waterborne or water-associated microbial pathogens in household drinking water supplies. However, fabric, paper and similar filters can be used in conjunction with coagulation processes or disinfection processes to achieve improved reductions of particles (turbidity) and microbes in water. Such combined or multi-step systems are described elsewhere in this report. Furthermore, the World Health Organization and the international health community strongly support the use of filtration with fabric, paper and other mesh filter media as an essential intervention to eradicate guinea worm (dracunculiasis).

4.7 Porous ceramic filters

Porous ceramic filters made of clay, carved porous stone and other media have been used to filter water since ancient times and were cited by Aristotle (322-354 BCE). Modern accounts of ceramic filters for household use date back to at least the 18th century (Baker, 1948). Most modern ceramic filters are in the form of vessels or hollow cylindrical "candles". Water generally passes from the exterior of the candle to the inside, although some porous clay filters are designed to filter water from the inside to the outside. Many commercially produced ceramic filters are impregnated with silver to act as a bacteriostatic agent and prevent biofilm formation on the filter surface and excessive microbial levels in the product water. However, all porous ceramic media filters require regular cleaning to remove accumulated material and restore normal flow rate. Porous ceramic filters can be made in various pore sizes and most modern ceramic filters produced in the developed countries of the world are rated to have micron or sub-micron pore sizes that efficiently remove bacteria as well as parasites. Many ceramic filters are composed of media capable of adsorbing viruses and in principle can achieve high virus removal efficiencies. However, because adsorption sites for viruses often become occupied by competing adsorbents, virus adsorption efficiency decreases with increased use and may become inefficient, unless physical or chemical cleaning procedures can restore the virus adsorption sites.

Porous ceramic filters are made of various mineral media, including various types of clays, diatomaceous earth, glass and other fine particles. The media are blended, shaped by manual or mechanical methods, dried and then fired at various temperatures to achieve different pore sizes and filtration properties. Some are unfired to maintain an open pore structure for filtration. Most ceramic filters are easy to use and are a potentially sustainable technology. The availability of suitable raw materials and the appropriate technology to blend these raw materials, shape the filter units and then perhaps fire them in a kiln are the main technical and accessibility barriers to their availability in developing countries. The need for inspection and other quality control measures, as well as appropriate testing for proper pore size are also important requirements for their production. Some units are brittle and fragile and therefore, can break during use. Broken filters, even if only slightly cracked, are unsuitable for removal of particles and microbial contaminants from water.

Ceramic filters for point-of-use water treatment are being produced and have come into widespread use in many parts of the world. Ceramic filters containing fired clay, limestone, lime and calcium sulfate have been produced for water filtration in Pakistan (Jaffar et al., 1990). These filters were found to reduce turbidity by 90% and bacteria by 60%. Ceramic filter candles that are 6 cm diameter and 11 cm long have been produced commercially in Cote d'Ivoire for less than US$10 (Ceramiques d'Afrique) and other low cost ceramic filters are being produced in different parts of the developing world with the assistance of the organization Potters for Peace. The extent to which ceramic filters being produced in the developing world have been or are being tested for reductions of waterborne microbes such as viruses, bacteria and parasites and their waterborne diseases in uncertain at this time. Such performance evaluation for microbial reductions would be valuable information and provide a basis verifying the quality of the filters. Ceramic filters manufactured commercially in various countries of the developed world, such as the United Kingdom and the United States of America, have been extensively tested for efficacy in reducing various waterborne microbial contaminants and many are certified for their performance microbial characteristics. Some of these are rated to remove at least 99.9999% of bacteria, such as *Klebsiella terrigena*, 99.99% of viruses, such as polioviruses and rotaviruses, and 99.9% of *Giardia* cysts and *Cryptosporidium* oocysts as required for Point-of-Use Microbiological Water Purifiers in the United States (USEPA, 1987). These filters tend to be more costly than most of those produced in developing countries, and therefore, their accessibility, affordability and sustainability for household water treatment by the poorest people in developing countries is uncertain at this time.

Overall, ceramic filters are recommended for use in water treatment at the household level. The main barriers to the production, distribution and use of fired or unfired ceramic filter-adsorbers are the availability of trained workers, fabrication and distribution facilities and cost. Further efforts are needed to define and implement appropriate manufacturing procedures and product performance characteristics of these filters in order to achieve products of acceptable quality that are capable of adequate microbe reductions from water. A simple and affordable method to test the quality and integrity of these filters also is recommended for use in situations where more technically demanding and costly testing is not available. . Quality and performance criteria and data for ceramic filters made in the developing world would provide a basis to judge quality and verify acceptable performance. However, the use of any intact ceramic filter to treat household water is likely to provide some improvement in water quality and therefore is preferable to no water treatment at all.

4.8 Diatomaceous earth filters

Diatomaceous earth (DE) and other fine granular media also can be used to remove particulates and microbial contaminants from water by so-called precoat and body feed filtration. Such filters have achieved high removal efficiencies of a wide range of waterborne microbial contaminants without chemical pre-treatment of the water (Cleasby, 1990; Logsdon, 1990). A thin layer or cake of the fine granular or powdery filter medium is precoated or deposited by filtration onto a permeable material held by a porous, rigid support to comprise a filter element. The water to be filtered often is supplemented with more filter medium as so-called body feed. As water passes through the filter, particulates are removed along with the body feed filter medium. This system maintains target flow rates while achieving high efficient particulate removal. DE filters also are capable of moderate to high pathogen removals (Logsdon, 1990). Eventually, the accumulation of impurities requires the removal of accumulated filter medium, cleaning of the filter medium support and reapplication of filter medium precoat to start the process over again. Although such DE and other precoat-body feed filter systems are used for small scale and point-of-use water treatment, they require a reliable, affordable source of filtration medium, regular care and maintenance, and they produce a spent, contaminated filter medium that may be difficult to dispose of properly. In addition, the filter media are difficult to handle when dry because as fine particles they pose a respiratory hazard. Because of these drawbacks, DE filters are not likely to be widely use for household water treatment in many parts of the world and in many settings, and therefore, they are not recommended for this purpose.

Table 11 Types, Performance Characteristics, Advantages and Disadvantages and Costs of Alternative Filters for Household Water Treatment

Filter Type	Advantages	Disadvantages	Comments
Rapid, Granular Media	See Table 8 above for details on these filters		
Slow Sand Filters	Useable on a small scale at community and maybe household level; relatively simple; can use local, low cost construction materials and filter media; relatively easy to operate manually; high turbidity and microbe reductions.	Requires some technical know-how for fabrication and use; initial education and training needed; requires user maintenance to clean and operate (materials, skill, labor and time).	Simple, affordable and appropriate technology at the community level; less appropriate for treating individual household water, unless by a collection of households.
Fiber, fabric and membrane filters	Usable at household level if filter media is available, easy to use and affordable	Wide range of filter media, pore sizes and formats; microbe removal varies with filter media; best used to remove large and particle-associated microbes; not practical, available or affordable for efficient removal of all waterborne pathogens	Has been effective in reducing guinea worm, *Fasciola* and schistosomiasis; can be coupled with other treatment methods (coagulation and disinfection) to improve overall microbe reductions
Porous ceramic filters	Simple and effective	Quality ceramic filters may not be	Greater efforts are needed to

	technology for use at the household level; extensive microbe reductions by quality filters; filters can be locally made from local materials, if education and training provided	available or affordable in some Quality of local made filters may be difficult to document unless testing is available to verify microbe reductions; need criteria and systems to assure quality and performance of filters	promote the development of effective ceramic filters for household water treatment in developing countries by adapting the local production of clay and other ceramic ware now used for other purposes to water treatment
Diatomaceous earth filters	Efficient (moderate to high) removals of waterborne pathogens	Not practical for household use; need specialized materials, construction and operations including regular maintenance; dry media a respiratory hazard	Pre-fabricated, commercial DE filters and media are available in some countries but high costs and low availability may limit household use in other places

4.9 Aeration

Aeration of water alone is simple, practical, and affordable, especially if done manually in a bottle or other vessel. Aeration of water as been practiced since ancient times and was believed to improve water quality by "sweetening" and "softening" it (Baker, 1948). It was later discovered that aeration indeed oxygenated anaerobic waters and that such a process would oxidize and precipitate reduced iron, manganese and sulfur, as well as strip volatile organic compounds, some taste and odor compounds, and radon. However, there is no evidence that aeration for brief time periods (minutes) has a direct microbiocidal effect. However, aeration of water introduces oxygen, which can cause chemical reactions, such as precipitation in anaerobic water containing certain dissolved solutes, and which can contribute indirectly to other process that may lead to microbial reductions. In addition, studies suggest that aeration has a synergistic effect with sunlight and heat on disinfection by solar radiation of water held in clear bottles. The mechanisms of this effect are not fully understood. However, they may involve conversion of molecular oxygen to more microbiocial chemical species by photooxidation reactions with microbial components or other constituents in the water, leading to photodynamic inactivation. Further studies of the ability of aeration to inactivate microbes in water either alone or in combination with other agents needs further study. Currently, there is no clear evidence that aeration alone is capable of appreciably and consistently reducing microbes in water.

5. Chemical Methods of Water Treatment

A number of chemical methods are used for water treatment at point-of-use or entry and for community water systems. These methods can be grouped into several main categories with respect to their purpose and the nature of the technology. The main categories to consider here are: (1) chemical pre-treatments by coagulation-flocculation or precipitation prior to sedimentation or filtration, (2) adsorption process, (3) ion exchange processes and (4) chemical disinfection processes. All of these processes can contribute to microbial reductions from water, but the chemical disinfection processes are specifically intended to inactivate pathogens and other microbes in water. Therefore, chemical disinfection processes appropriate for household water treatment in the developing world will be the focus of attention in this section of the report. Other chemical methods for water treatment will be examined for their efficacy in microbial reductions and their applicability to household water treatment.

5.1 Chemical coagulation, flocculation and precipitation