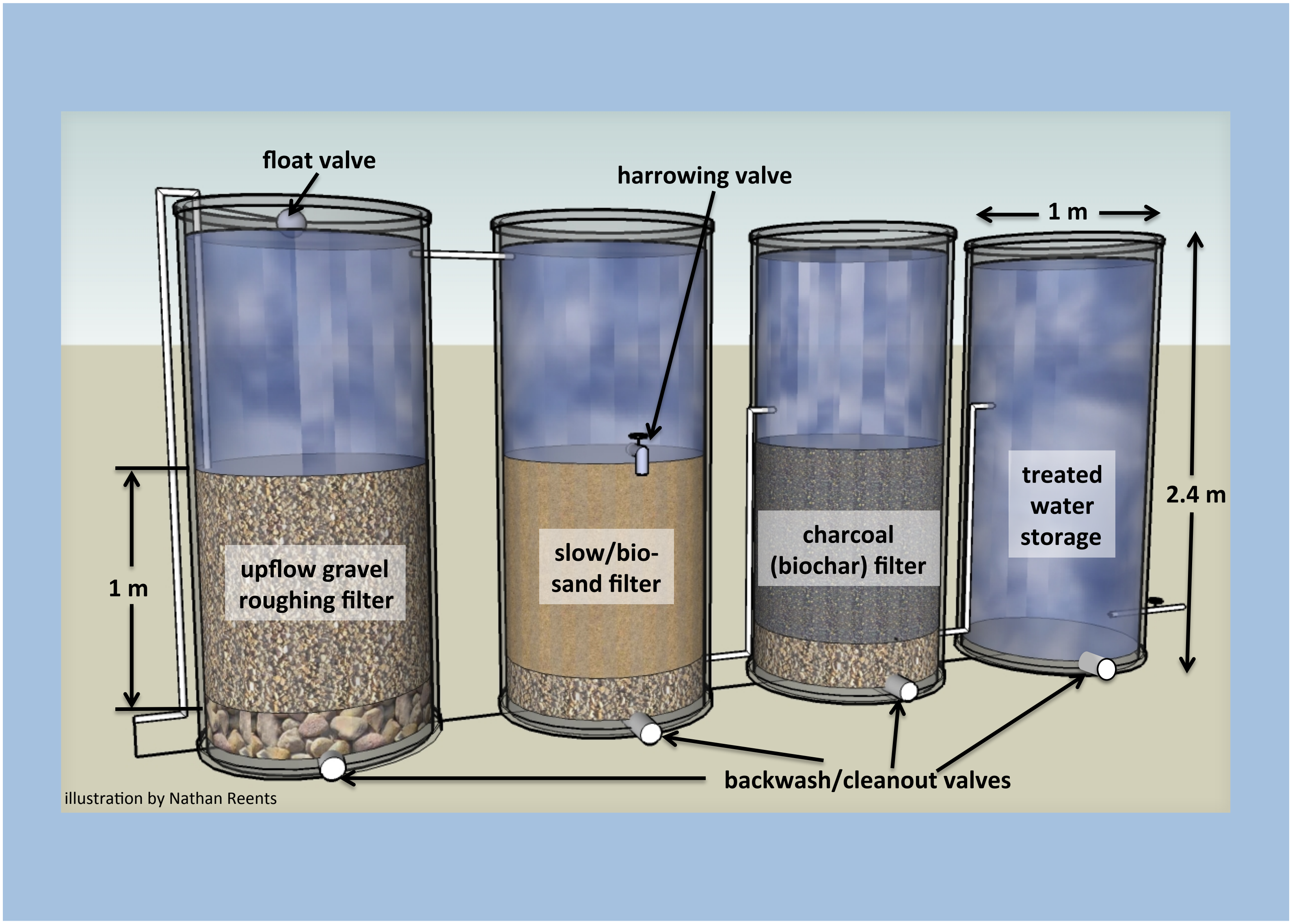
Constructing A Multi-Barrier Water Treatment System Using Local Materials



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Introduction

Contamination of drinking water sources by disease causing microbial agents and chemical toxicants such as pesticides, pharmaceuticals, industrial wastes and fuel components is a growing worldwide problem. Microbiological water contaminants cause diarrhea, flu and other diseases. Many synthetic chemical contaminants bio-accumulate in the human body and cause cancer, birth defects and diseases of the reproductive system, and disrupt endocrine and neurological systems.

For rural households and small communities, low-cost decentralized water treatment for removal of biological and chemical contaminants can be accomplished using widely available local materials. Here we provide detailed instructions for construction of a multi-barrier intermediate-scale (up to 2000 L/day) water treatment system using a series of gravel, biologically active sand and char filters. The system costs around $500 to construct, and should provide years of service withperiodic maintenance of the bio-sand filter and char refurbishment every 2-3 years.

The information and design specifications presented here are open source / open architecture. We invite critical feedback from field engineers and WASH (water-sanitation-hygiene) sector development practitioners, university researchers, sustainable development NGOs, community water technicians, etc. Please contact **josh@aqsolutions.org** to find out more.

Terminology and Abbreviations

Adsorption / Absorption / Sorption
"*Ad*sorption" signifies a surface interaction between dissolved species and solid material (in this case, char). This process is distinct from "*ab*sorption," which means "to soak up" or "to take into." To be exact, however, in water treatment contaminants diffuse into char pores (*ab*sorption) where they bind to char surfaces (*ad*sorption). This has led wide use of the nonspecific term "sorption."

Biochar / Charcoal / Char
"Biochar" refers to the practice of applying charred biomass to agricultural soils in order to increase crop yields, and/or to sequester carbon in the soil. "Charcoal" refers to a biomass-derived char product most often used as cooking fuel. "Char" is a nonspecific term used for convenience referring to biochar or charcoal.

Biomass / Feedstock
Here, "biomass" refers to any woody or cellulosic material (e.g. wood, agricultural and forestry residues) that serves as the precursor, or "feedstock," for making char.

Micro-porosity / Surface Area
A "micro-porous" material possesses very fine pore structure at the nanometer to micrometer (10^{-9} – 10^{-6} m) scale. "Surface area" refers primarily to internal surface area, i.e. within micro-pores.

Pathogen
Human-disease-causing waterborne microbiological agent.

AC/GAC	activated carbon / granular activated carbon
BSF / SSF / S-BSF	biological sand filter / slow sand filter / slow biological sand filter
SOC	synthetic organic compound
WASH	water-sanitation-hygiene

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Improving water quality involves mitigating disease causing biological agents (pathogens) as well as harmful chemical contaminants and non-harmful compounds that impart an unpleasant taste, odor, or appearance. Pictured on the cover of this report is a multi-barrier water treatment system that addresses these challenges using a sequence of gravel, biologically active sand and char filtration. A system built according to these specifications can provide 1500-2000 L/day of treated water depending upon source water quality.

I. Siting and materials

a) *Siting*

Gravity is the easiest and most dependable way to move water. Ideally, the water system is sited on stable, level ground at lower elevation than the source water and higher elevation than the location(s) where treated water will be used. This circumstance enables completely passive operation of the treatment system and very simple control using only a float valve (the same device that refills the tanks of flush toilets): when water is withdrawn from the storage tank the water level in the system drops, opening the float valve. When the system is full, the float valve closes.

b) *Containment*

In SE Asia, stackable prefabricated concrete rings are inexpensive and widely available in most rural areas and are commonly used for tank construction. Rings are mortared together with concrete and the tank interior walls sealed with cement slurry. Filling the tank with water when the slurry is still wet pushes it into pores to cure and seals the tank.

Plastic tanks can also be used, or, if appropriately skilled masons are available, custom ferro-cement tanks can be constructed. Tanks need to have a large opening and removable lid so that a person can fully enter for connecting plumbing, installing filter media, conducting routine maintenance (which includes cleaning tank interiors and removal/replacement of the char), and for repairs.

Lids or some cover material to exclude sunlight should be used to inhibit the growth of photosynthetic microorganisms (algae, cyanobacteria) in the system. Tank tops should be wrapped in fine mesh screening to prevent entrance of insects, bird droppings, leaves and bits of debris, etc. into the system.

Tanks should be constructed on a solid and level foundation (preferably of reinforced concrete), and distinguished from other similar-appearing water tanks (e.g. rainwater, irrigation water, septic, etc.) using appropriate and durable local signage.

c) ***Plumbing***

PVC pipe is ubiquitous and cheap in most locations. 1/2” to 3/4” diameter is fine for most connections to and from the water system and between the tanks. The cleanout valves at the bottoms of the tanks should be larger, typically 3” to 4”. 1” to 2” is ideal for the harrowing valve midway up the sand filter tank.

Plumbing in the bottom of filter tanks should be protected from physical damage and blockage by underdrains made from rock and coarse gravel at least 20 cm in depth. Sand and char filter media should be supported by an additional graded underdrain made from pea gravel overlain by coarse sand (at least 10 cm deep of each).

The connection from the gravel filter to the sand filter should be located near the top of the tanks, a few cm below the full-position water line (set by adjustment of the float valve). The connection from the sand filter to the char filter should enter the char tank at a level about 5 cm above the level of the sand – i.e. at a height of about 145 cm above the bottom of the tank if a 40 cm underdrain is used with 1 m of filter media. The same is true for the connection from the char filter to the storage tank. This ensures that the water level in the sand and char filters will never drop below the level of the filter media. This is essential for maintaining full vigor and functioning of the biofilm in the sand filter, and for utilizing all of the sorption capacity of the char filter.

d) ***Media***

Standard gravel (1-4 cm sized rocks) is fine for the roughing filter. Standard fine sand (as opposed to coarse or very fine sand) should be used for the sand filter. Sifted sand or masonry sand are very fine and may generate too much head loss, especially if source water contains a lot of organic matter. Large pieces of charcoal should be broken into 1-5 cm pieces. Gasifier char can be used directly since feedstocks are small or pre-cut materials.

II. How it works… (and how to maintain it…)

a) *Gravel roughing filter*

Source water (controlled by the float valve) enters by a pipe at the bottom of the gravel filter and flows upward through the media. This removes turbidity (particles) and some dissolved matter that sticks to the surfaces of particles as they settle. One or more times during the year (depending upon source water quality), the large valve (at least 3" – bigger is better) at the bottom of the gravel filter is opened, rapidly reversing the direction of flow through the filter ("backwashing") in order to flush out the accumulated sediment and organic matter.

Gravel filter maintenance: As long as the plumbing does not break, or the plumbing or media become irremediably clogged by sediment or debris, the gravel does not need to be removed or replaced within the lifetime of the treatment system. Some "MacGyvering" may be necessary to ensure that the outlet of the float valve completely directs influent water into the pipe leading to the bottom of the tank. The float valve should be periodically examined for potential clogging or misdirection of influent water.

b) *Slow/bio- sand filter*

Sand filters remove microorganisms and particles by physical straining, and some dissolved compounds by adsorption onto the surfaces of sand grains. Most importantly, however, biologically active sand filters remove problematic microorganisms and chemical compounds by biodegradation. Unless a disinfectant such as chlorine is added to the system, a biofilm (or *schmutzdecke*) naturally develops within a few days upon beginning use of the filter, and continues to mature over a period of several weeks. The length of this time period, termed "ripening," depends primarily upon ambient temperature and source water characteristics.

The biofilm is concentrated in the top 1 to 3 cm of the media (though exists more sparsely throughout the sand bed) and actively degrades dissolved organic compounds in the influent water. The natural environmental microorganisms that comprise the biofilm prevent the establishment of microbial pathogen colonies through competition and predation. Thus sand filters with healthy established biofilms are an effective and well-demonstrated technique for removal of pathogens as well as some hazardous biodegradable compounds in water treatment.

A note on BSFs and SSFs and S-BSFs… Readers may be familiar with smaller (family sized) rapid rate "BioSand Filter (BSF)" units promoted for household water treatment in developing communities, as well as conventional large-scale slow sand filters (SSF) used by municipal drinking water utilities in developed areas. The slow/bio- sand (S-BSF) filter presented here is an intermediate design adapted to address some of the respective limitations of BSFs and SSFs.

In short, in sand filters a longer contact time between the water and sand/biofilm provides better treatment by allowing more time for adsorption and biodegradation mechanisms to occur. However, increasing contact time requires a larger filter unit to treat a similar volume of water, incurring greater construction costs and occupying a larger "footprint" for the treatment system. Furthermore, a slow and steady loading rate (as opposed to a rapid, intermittent loading rate as in household BSFs) contributes to better biofilm function and enhanced treatment as this establishes a quasi-steady-state influx of nutrients to the biofilm.

The S-BSF unit process described here combines a low and more consistent loading rate for optimal contact time with the biofilm and media to achieve effective pathogen removal and contaminant biodegradation, while providing sufficient total throughput of treated water in an economical, small-footprint design.

Slow/bio-sand filter maintenance: The sand filter is the "bottleneck" step (i.e. the flow-rate-determining step) of this water system. As organic material accumulates in the biofilm zone at the top of the sand bed, flow rates may diminish below a minimum threshold of treated water needed by the community. Thus a few times per year it may be necessary to "wet harrow" the sand filter to restore sufficient flow rates. This is accomplished using a long pole to vigorously stir up and suspend the accumulated sediment from the top few centimeters of sand into the water above the filter bed. The harrowing valve (located 5 to 10 cm above the top level of the sand) is then opened to allow the suspended sediment and organic material to wash rapidly out of the upper portion of the tank. The majority of the suspended sand particles are not washed out but resettle, and the biofilm reestablishes full function within a few days. A small amount of sand is washed out during harrowing and after several maintenance cycles it may be necessary to replace some sand to the top of the filter bed.

The frequency of wet harrowing required to maintain adequate flow rates is determined by the community's water needs and the characteristics of the source water. Since the sand filter is the rate-limiting of the treatment system, increased throughput can be achieved by increasing the size (cross-sectional area) of the filter in the original design, or by building additional units in parallel.

c) ***Charcoal (biochar) filter***

Terminology and key concepts The char filter functions primarily by the process of adsorption. *Ad*sorption, which signifies a surface interaction between dissolved species and the char, is distinct from *ab*sorption, which essentially means "to soak up" or "to take into." To be exact, however, in water treatment contaminants diffuse into char pores (*ab*sorption) where they bind to char surfaces (*ad*sorption). This has led wide use of the nonspecific term "sorption."

The porosity and large surface area of chars provides a multitude of reactive sites for the attachment of dissolved compounds. These reactive sites can bind non-problematic dissolved organic compounds as well as targeted hazardous contaminants. Background dissolved organic matter, present in all natural waters, can occupy sites on char surfaces and thereby exclude contaminants of concern. This is called "fouling." Fouling in char filters is mitigated by upstream unit processes – in our case, the gravel and sand filters – that act to remove a substantial portion of background dissolved organic matter from the source water before it encounters the char. The principle is to achieve a high level of treatment prior to the char filter, in order to "save the carbon" for removal of targeted problematic dissolved compounds that make it through the previous treatment steps.

Local chars versus activated carbon In treatment system described here, the char filter functions as a "post-filter adsorber," analogous to the use of granular activated carbon (GAC) unit processes in advanced municipal water treatment facilities. The char filter is placed after the gravel and sand filters in order to target specific components of background organic matter (for example, compounds that cause undesirable tastes, odors, or appearance) or synthetic organic compounds (SOCs) such as pesticides, pharmaceuticals, fuel compounds, etc., that are not well removed by the preceding unit processes.

There are, however, a few important differences between locally generated charcoals/biochars and commercial activated carbon. First, local chars are (ideally) made from agricultural and forestry residues and sustainably harvested renewable woody biomass. Most commercial activated carbons are made from (nonrenewable) subbituminous and lignite coal. Both local chars and activated carbons undergo a carbonization step where the feedstock is heated to several hundred degrees Celsius under restricted oxygen atmosphere. However, commercial carbons are subsequently "activated" by physical and/or chemical processes to develop the internal pore structure and surface reactivity using high-pressure steam, CO_2, or acids. In other words, the activation step is an industrial process requiring facilities, power, equipment and reagents that are not accessible in developing communities.

Furthermore, compared with activated carbon, local chars may contain substantial proportions of residual incompletely carbonized tarry and oily compounds, particularly if the char is generated at lower temperature (i.e. below ~ 600 °C, as in cooking charcoal manufacture). Local chars may also contain a high proportion of ash if the feedstock consisted of high mineral content grasses or husks (e.g. rice hulls). Since local chars are not "activated" and may contain higher proportions of ash or residual tars and oils, they are not expected to exhibit the same water treatment capacity as commercial/industrial GACs. This disparity is compensated by designing for higher carbon use-rates (i.e. the mass of carbon used to treat a given volume of water).

Carbon bio-filtration In the char filter as in the sand filter, if no disinfectant is added to the system then a natural biofilm readily develops on the surfaces of the filter media. This is generally a good thing. While the biofilm adds to the influx of natural organic matter in the system and thus may contribute to fouling, the environmental microorganisms making up the biofilm prevent the development of pathogen colonies in the media through competition and predation.

Furthermore, recent research on biological activated carbon filters has shown synergism between adsorption and biodegradation mechanisms for enhanced removal of SOCs. The efficiency of the combined adsorption-biodegradation process is higher than either adsorption or biodegradation processes alone. Adsorption by the carbon attenuates dissolved contaminants allowing time for their breakdown by the biofilm, which in turn frees up surface sites on the carbon for additional sorption, extending the life of the filter media. Even some compounds typically classified as non-biodegradable are broken down in long-running carbon bio-filters. Exposure to contaminants retained by the carbon over periods of weeks to months allows microorganisms to acclimate and develop the enzymatic pathways necessary to break down some otherwise environmentally recalcitrant compounds. Thus the synergy between adsorption and biodegradation processes can result in a net elimination of some hazardous SOCs from the system.

Contaminant leaching and spent carbon processing An often-raised concern for carbon filtration is the back-diffusion, or "leaching," of contaminants out of the carbon, either during its lifetime in the filter bed or afterwards during the disposal phase. Recent research on activated carbon systems has shown very little leaching to occur. Rates of back-diffusion (contaminants being released from surfaces and exiting through pores) are very slow due to pore blockage by natural organic matter. Essentially, contaminants diffuse into pores, attach to pore interior surfaces, and are trapped there by incoming natural organic matter that blocks pores over the operational lifetime of the filter. Moreover, most synthetic organic contaminants bind more strongly to carbon surfaces than dissolved background natural organic matter – so natural organic compounds are unlikely to displace adsorbed contaminants.

This suggests that the release of adsorbed contaminants from char should not be a great concern, either during the use phase in the char filter or subsequently in the disposal phase. As indicated in bio-filtration studies, time and the metabolic activity of microorganisms are the most effective means for breaking down sorbed contaminants. In the rural or developing community context, this can be accomplished through composting the spent filter char and then applying it to agricultural soils in the manner advocated by biochar practitioners. A conservative approach to land application of spent filter char can also be adopted, using low incorporation rates of ~ 100 kg of char per hectare.

Char filter refurbishment The effective lifetime of the char filter media depends upon the quality of the char, as well as the characteristics of the source water and efficacy of upstream treatment steps. In the rural developing community context, these factors are typified by high degrees of variability and uncertainty. Since char can be generated locally and inexpensively a conservative approach is recommended, designing for a much larger carbon use-rate than is employed in advanced GAC systems. A char filter built according to the specifications outlined here and supplying 2000 L/day should be refurbished at least every 2-3 years.

This estimate should be taken as a rough guideline. Ongoing research at Aqueous Solutions and with our collaborators is refining filter system design specifications and recommended operation protocols. However, it is ultimately up to the discretion of the community and water system operator(s) to consider factors such as variability in community water demands and seasonal source water quality concerns (e.g. turbidity and dissolved organic matter increase during the rainy season, local agricultural cycles and pesticide application periods, nearby industrial development that may impact source water, etc.) in determining an appropriate char filter bed lifetime and change-out frequency for each installation.

d) *Safe water storage*

The storage tank should be sized to meet the water needs of the community with an appropriate buffer. Great caution must be exercised to ensure that treated water is not re-contaminated during storage, in the distribution system, or in water receptacles such as jerrycans used by community members.