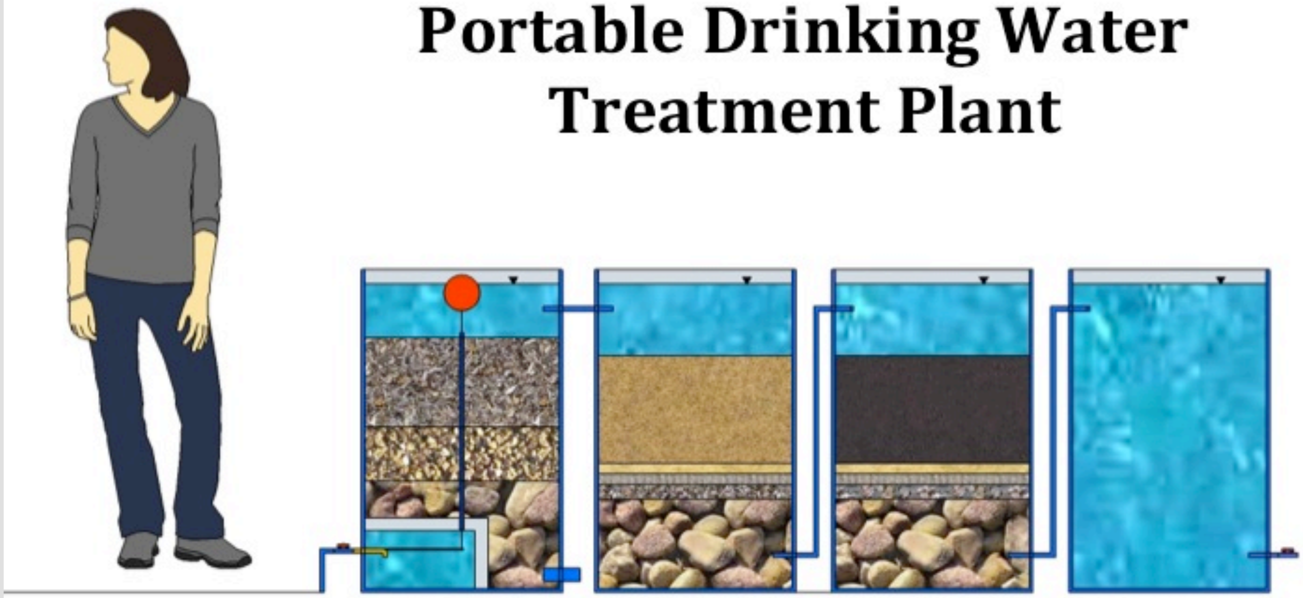
Portable Drinking Water Treatment Plant



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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 households and communities in remote areas, low-cost decentralized water treatment for removal of biological and chemical contaminants can be accomplished using filter media generated/acquired locally. Here we provide detailed instructions for construction of a portable drinking water treatment plant providing up to 300 L/day using a series of gravel, biologically active sand and char filters. Containment is provided by four 200 L BPA-free HDPE (high density polyethylene) drums. Empty drums weigh less than 10 kg and can be carried into remote communities on foot, connected with a small number of PVC fittings, and filled with media generated on-site and acquired nearby. The system costs about $125 to construct, and should provide years of service with periodic maintenance of the bio-sand filter and char refurbishment once per year.

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

<u>Ad</u>sorption / <u>Ab</u>sorption / 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

Constructing A Portable Water Treatment System Using Local Materials

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 handbook 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 up to 300 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. The water system should be sited on stable, level ground, and 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. Plumbing connections should be protected from accidental damage, and the entire system should be shaded to prevent degradation of plastic components by sunlight.

b) *Containment and plumbing*

The following parts and tools are required for installation of the water system:

PLUMBING PARTS SUMMARY	TOTAL QUANTITY
hoseclamp	12
hosebarb	12
3/4" valve	2
3/4" T	2
3/4" female coupler	2
200 L HPDE drum	4
1/2" valve	14
1/2" T	5
1/2" male coupler	8
1/2" female coupler	19
1/2" endcap	3
1/2" elbow	6
1/2" - 3/4" coupler	3
1-1/2" or 2" male end screwcap	1
1-1/2" or 2" male coupler	1
1-1/2" or 2" female coupler	2

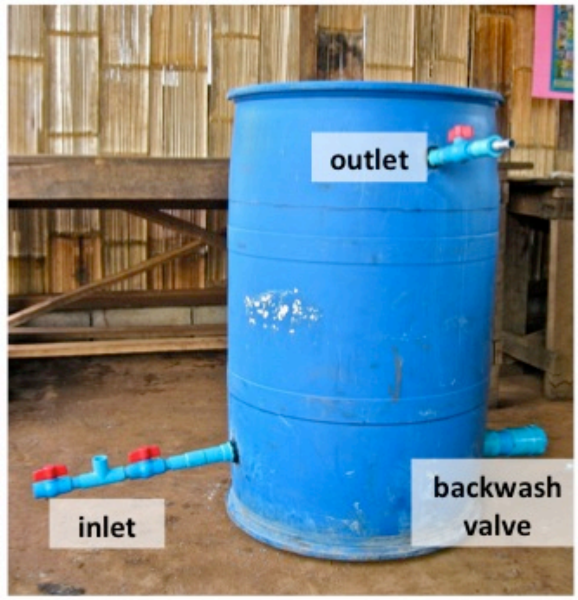
OTHER HARDWARE	DESCRIPTION	QUANTITY
1/2" PVC pipe	4 m length section	2
1-1/2" or 2" pipe	need only one small section 3" - 4" long	1
PVC glue	small tins	4
teflon tape	get the good quality thicker type	4
nylon twine	thin but strong	1 skein
screen	window screen or poultry netting OK	5 m
shade cloth	plastic is fine	4 m
wire	med. gauge, Al or steel	1 kg (>10 m)
flexible tubing	5/8" dia. or thereabouts	4 - 5 kg or 50 - 60 m
sand paper	med. grit	1 sheet
float valve	probably a 3/4" connection	1
bolt, nut and two washers	to fit float valve armature	1 set
silicone sealer		1 tube

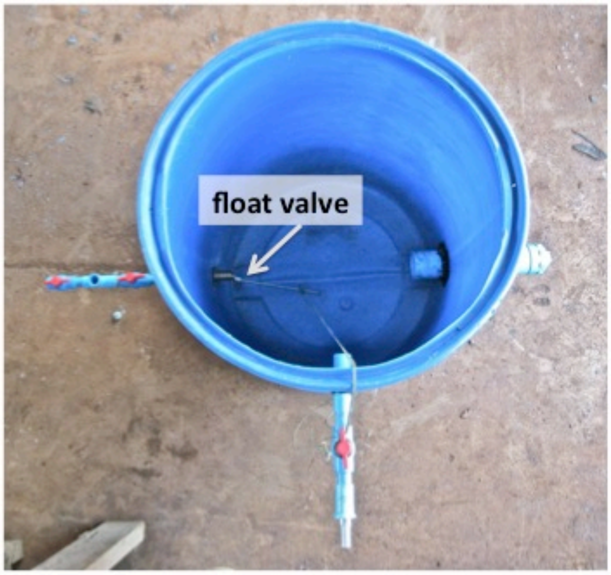
The above plumbing parts summary includes PVC fittings for connecting the water system to existing water supply and point-of-use infrastructure, as well as a number of recommended spares. Tools required include a sharp pocketknife and serrated blade for cutting PVC, a tape measure, paintbrush for applying silicone and PVC glue, and a permanent marker. A common vegetable steamer pan with holes ~16 mm (1/2") is useful for sieving gravel to obtain the pea gravel fraction.

PVC connections are installed in the HDPE drums using a knife to carefully cut holes the diameter of ½" male PVC threaded couplers. Connections should be snug enough that the male couplers are screwed into drums, helping to minimize leaks. Silicone is applied to male-female couples spanning tank walls also to help prevent leaks. Liberal use of Teflon tape on all threaded connections is highly recommended.

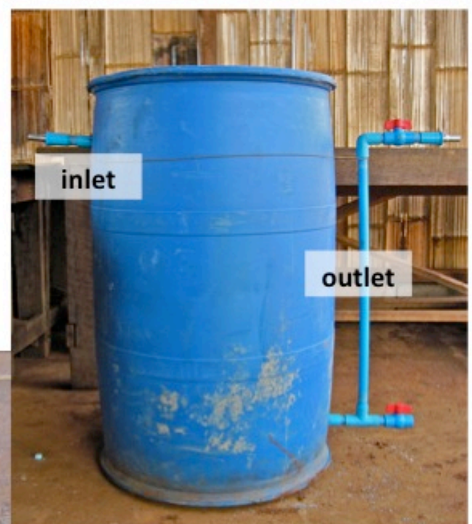
The following diagrams show plumbing connections for each tank and list the necessary parts.

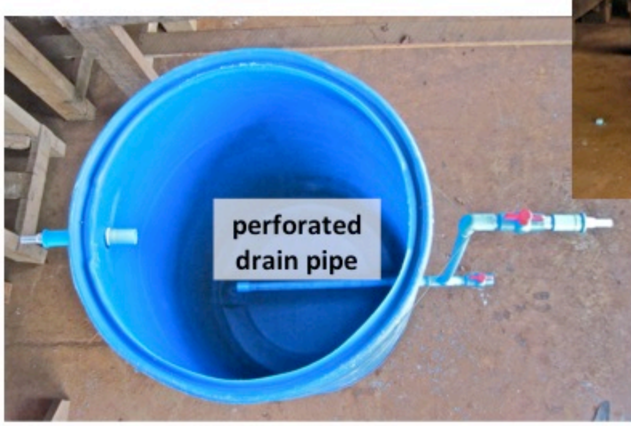
COMPONENT	PART	QUANTITY
gravel filter	200 L HPDE drum	1
	1/2" valve	3
	1/2" T	1
	1/2" - 3/4" coupler	1
	3/4" female coupler	1
	1/2" male coupler	1
	1/2" female coupler	2
	hosebarb	1
	hoseclamp	1
	1-1/2" or 2" male coupler	1
	1-1/2" or 2" female coupler	2
	1-1/2" or 2" male end screwcap	1



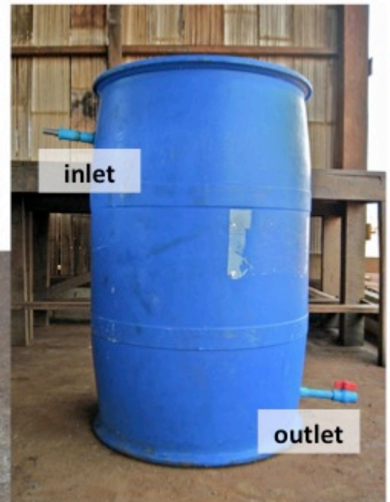


COMPONENT	PART	QUANTITY
sand / char filters	200 L HPDE drum	1
	hoseclamp	2
	hosebarb	2
	1/2" female coupler	4
	1/2" male coupler	2
	1/2" T	1
	1/2" valve	2
	1/2" elbow	1
	1/2" endcap	1





COMPONENT	PART	QUANTITY
treated water res.	200 L HPDE drum	1
	hoseclamp	1
	hosebarb	1
	1/2" female coupler	3
	1/2" male coupler	2
	1/2" valve	1

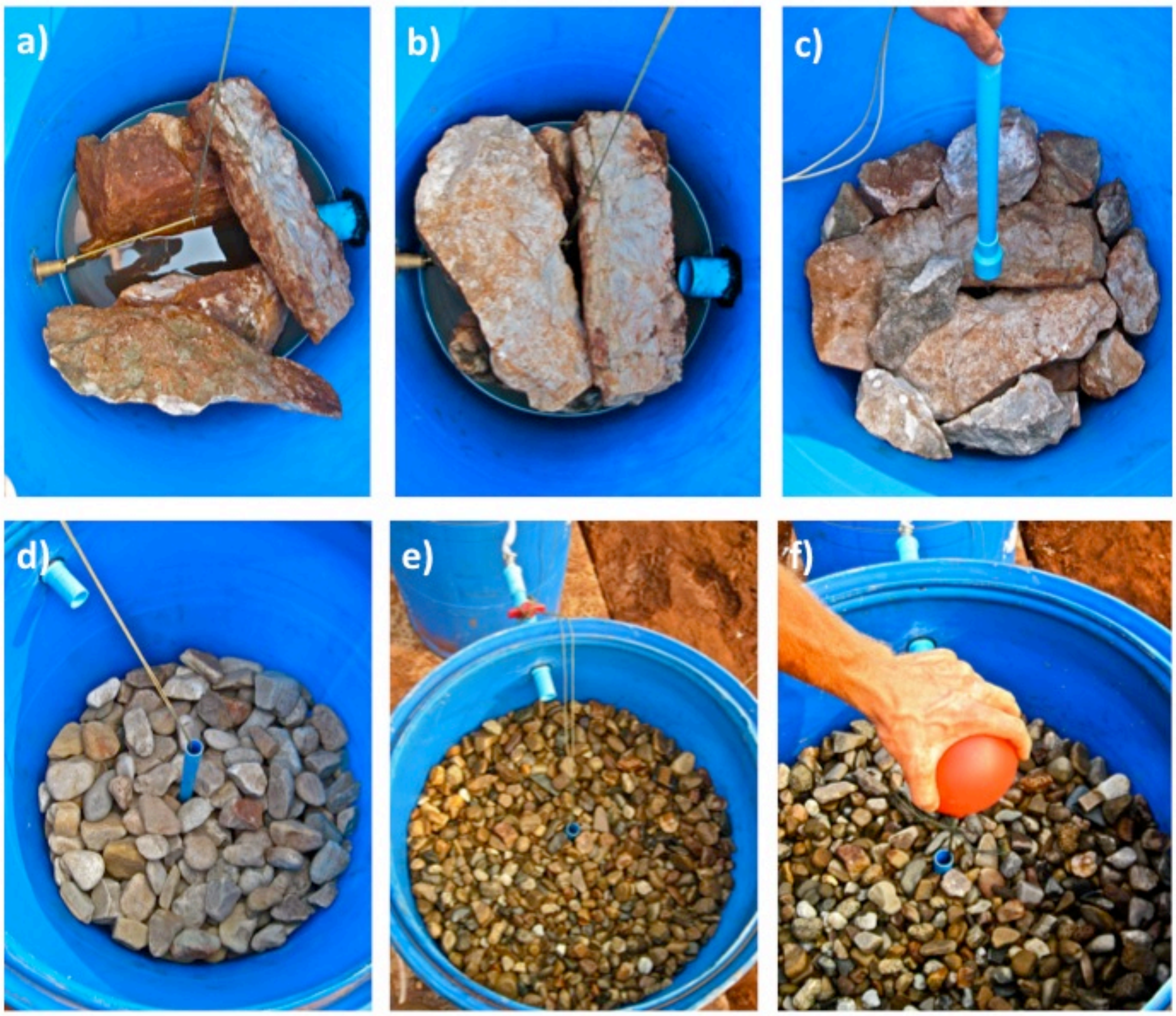


The outlet from the gravel filter should be located near the top of the tank, a few cm below the full-position water line (set by adjustment of the float valve). The outlet from the sand filter to the char filter should enter the char tank at a level about 5 cm above the level of the sand. The same is 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 top surface 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.

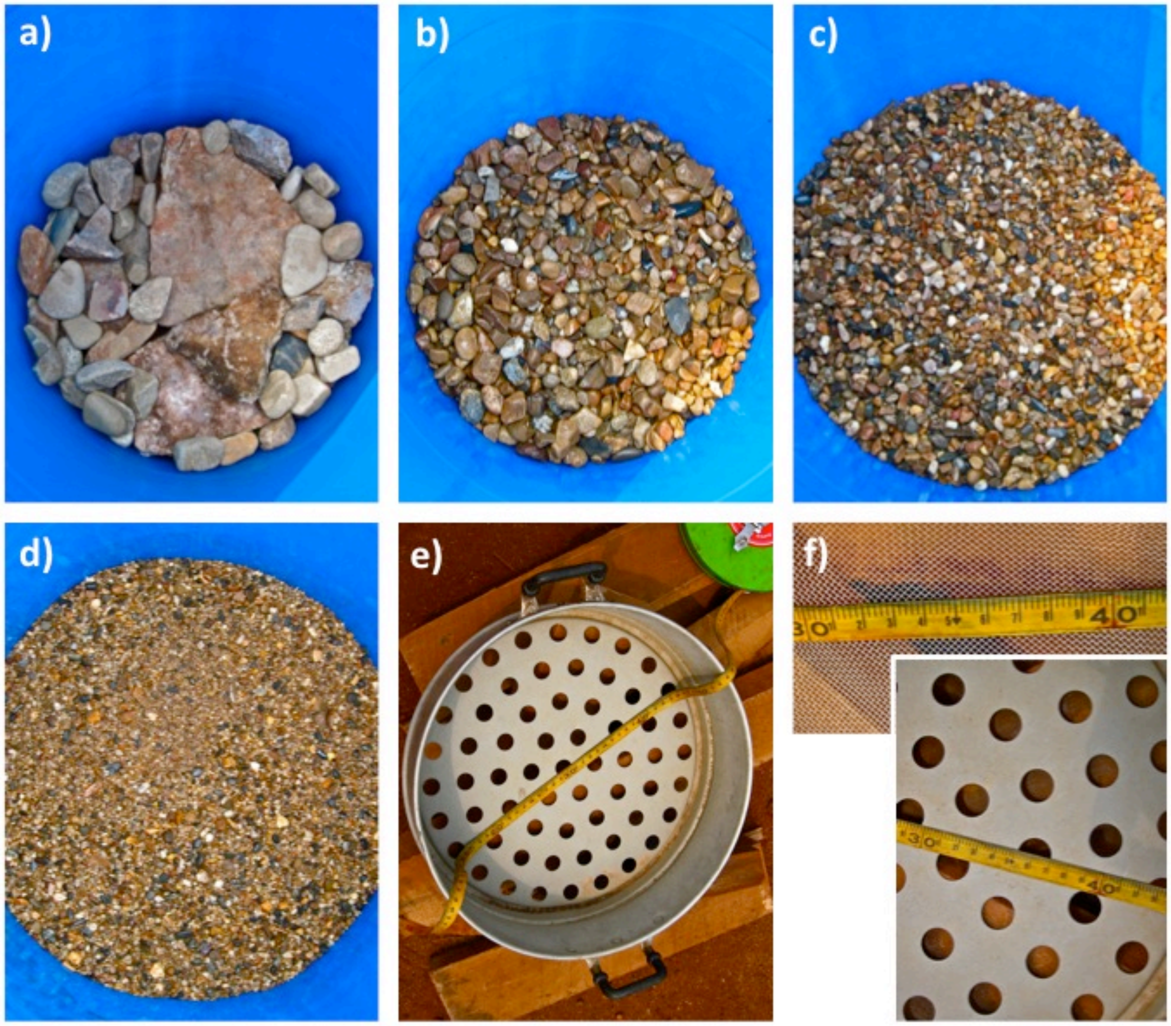
Tanks are connected in series using 15-20 cm sections of flexible tubing secured with hoseclamps. This, along with the valve configuration shown, allows tanks to be easily isolated and disconnected for maintenance. Screening the tops of tanks excludes debris, insects, etc. Shade cloth folded to several layers thick excludes sunlight in order to inhibit the growth of photosynthetic microorganisms (algae, cyanobacteria) in the system. The entire system should be shaded from direct sunlight, which can degrade plastic fittings and facilitate microbial growth. Inlet/outlet connections should be oriented unobtrusively and/or protected from accidental breakage using stones or other objects.

c) *Media*

The diagram below shows installation of the gravel and float valve. Large rocks are used to protect the float valve armature ((a) and (b)). A ½" PVC pipe fitted with a ½"-1" coupler is used to house the nylon string connecting the float valve armature to the floater ((c) and (d)).

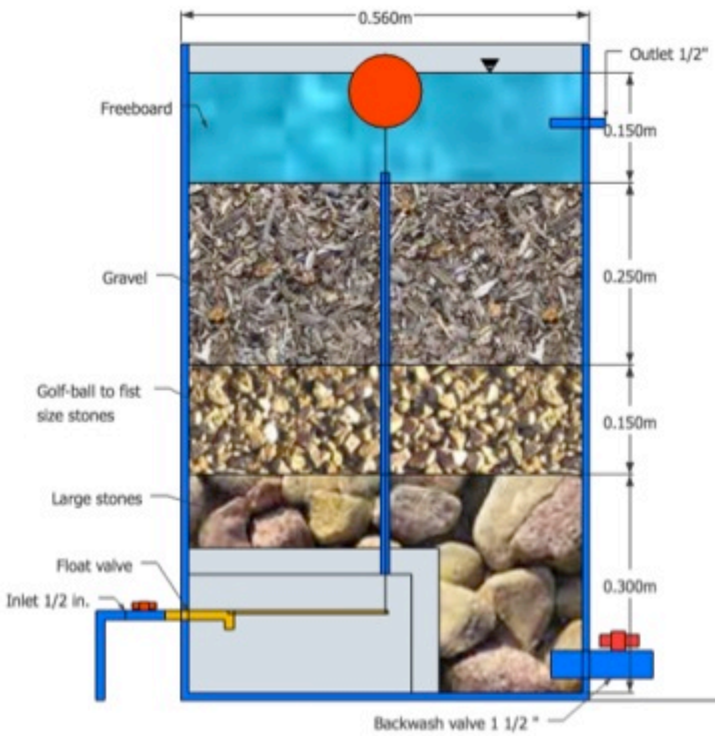


The diagram below shows construction of the underdrain system for the bio-sand and char filters. Large stones are used to protect the slotted drainpipe (a). The bottom ~ 30 cm of the tank is then filled with sequential layers of gravel (b), pea gravel (c), and coarse sand (d). A common vegetable steamer with holes ~ 16 mm dia. ((e) and (f)) can be used to sieve mixed river gravel to obtain pea gravel fraction. Window screen (f) or poultry netting can be used to sieve sand to obtain coarse and fine fractions.

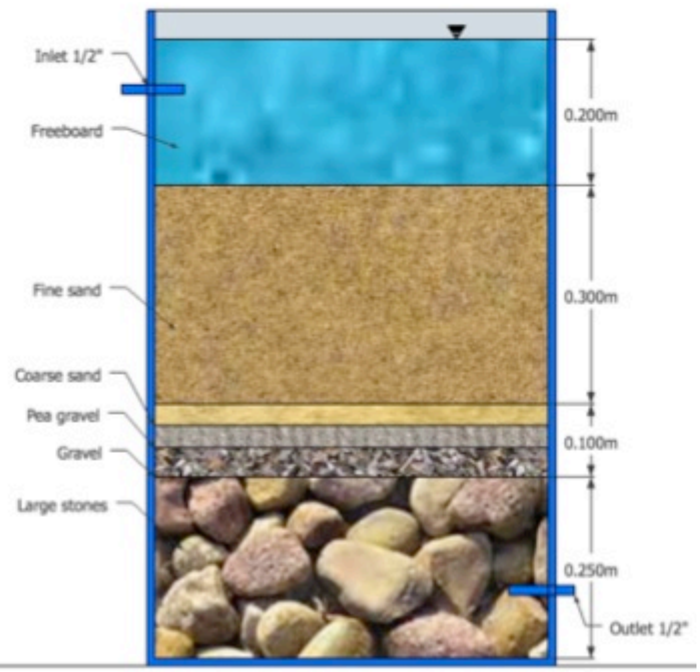


Fine sand or char are then placed in a layer 30-40 cm thick on top of the underdrain, leaving ~15 cm of freeboard. Water level throughout the system is controlled by setting the height of the floater in the gravel filter. Freeboard should be maximized to make full use of system volume and provide maximum head for moving water through the system. The diagram below indicates appropriate depths for underdrain and filter media.

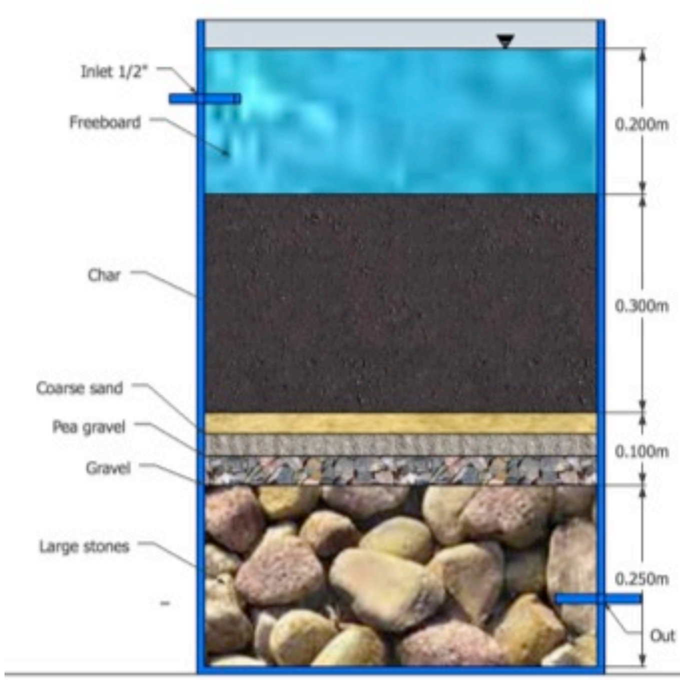
upflow gravel filter



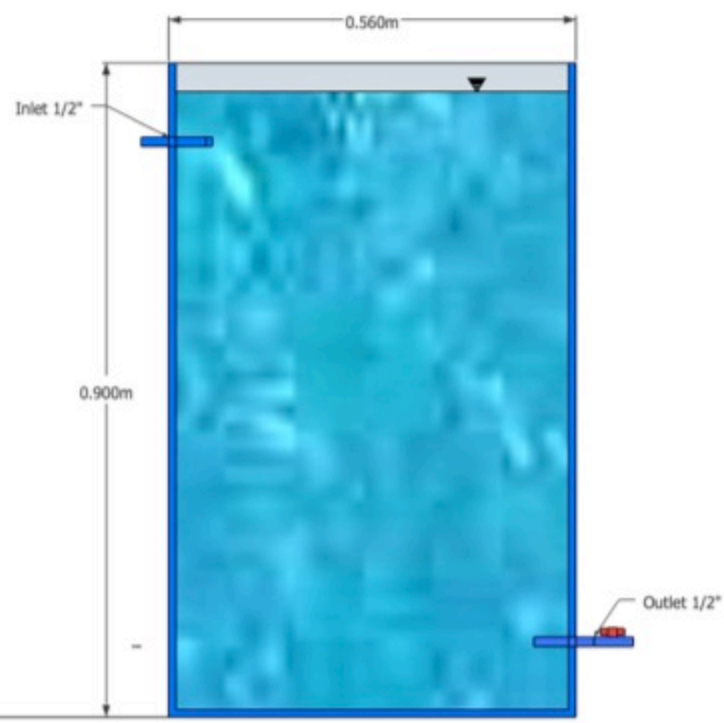
bio-sand filter



char filter



clean water storage



Illustrations by Nathan Reents.

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 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. The outermost ½" valve on the tank inlet can be used to backflush accumulated solids out of the T-inlet/float valve assembly.

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 intermittent, 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 by stirring up the water layer above the sand filter in order to suspend the accumulated sediment from the top few centimeters of sand. This cloudy water is then scooped out of the sand filter and discarded, and the filter allowed to refill. This process can be repeated two or three times as needed to restore adequate flow through the sand. The biofilm will reestablish full function within a few days and the system should not have to be taken offline. 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 step of the treatment system, increased throughput can be achieved by building additional sand filter units operating 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. increasing 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 300 L/day should be refurbished at least once per year.

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.

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