SLOW SAND FILTRATION WITHIN RAINWATER TANKS

Celia Way & Terry Thomas
University of Warwick
Engineering Department, Coventry, CV4 7AL, UK
c.m.way@warwick.ac.uk, t.h.thomas@warwick.ac.uk

ABSTRACT

Slow sand filtration is a long-established technique for improving the biological and physical quality of water. In its standard form water is passed at about 200mm/hour down through a bed of sand about 1 metre deep. For use inside a household rainwater tank however we require a much cheaper and therefore shallower filter and we must accommodate the intermittent flow corresponding to water being drawn off for a few minutes several times a day. A tenth-scale model of such a filter was built in the laboratory and used to show that very shallow sand filters (as little as 5cm deep) are effective even when they are operated very intermittently – reductions in faecal coliform count of about 95% were obtained. Some field tests in Uganda then followed which confirmed the effectiveness of the technique. The paper describes the findings and also examines how slow-sand filtration could actually be incorporated in rainwater tank design.

INTRODUCTION

Rainwater harvesting provides water that is generally of good chemical quality and is soft, suiting it for use for laundry and washing. Rainwater is slightly, but safely, acidic at first, but storage in mortar tanks can make it alkaline. The biological water quality found from rainwater harvesting is fairly good, but variable, particularly straight after rain has fallen. A. Pacey and A. Cullis[i] have shown that there is some bacteriological contamination of water from roofs. 'Often it is very slight…[but] such findings may not always be very significant because conditions in the storage tank or cistern are more critical than conditions on the roof'. Intercepting the water between roof and tank may not therefore be the most effective way of improving final water quality.

There are three main steps that can be taken to improve water quality:

1. Treatment of water prior to its entry into the tank. This could be done by: screening, fast filtering (for a small house, the roof runoff flowrate can be up to 1.5 litres/sec), passage through a buffer (sedimentation) tank, or first flush diversion (diverting the initial runoff, the dirtiest water that may be collected).

2. In-tank processing. Typically this is done by sedimentation and the use of a floating take-off collection valve. Utilising a chlorine-disinfection method is a possibility, perhaps by dosing the tank with chlorine releasing compounds. Any technique for encouraging a 'plug-flow' of water into, through and out of the tank will improve bacteriological quality of the water, as opposed to 'fully-mixed flow'. It must also be ensured that pollution from buckets/ vessels being dipped into the water, or vermin entry, is minimised by intelligent tank design.

3. Post-storage processing. Having withdrawn water from the tank, it may then by treated in many conventional ways, for example boiling, solar water disinfection (SODIS), chemical disinfection or micro-filtration.

Stage 1 treatment is traditionally strongly recommended, because it reduces bacteria and decreases the need for tank cleaning. However, in a realistic situation, it may not suffice. Stage 3 treatment is tedious and time consuming for the water user. It may also prove expensive, and whilst being recommended by public health authorities, it is rarely practiced in rural areas of developing countries. Stage 2 treatments have the appeal of being designed into the system and able to proceed relatively slowly – several hours usually separate the inflow and exit from the tank. Even the exit flowrate can be very low, 50 seconds to fill a bucket is probably acceptable, equating to 0.2 litres/second.

A type of Stage 2 treatment that is virtually never used in this situation is slow sand filtration, a process that in a different context is well known to give great improvement to the bacteriological quality of water.

The primary requirement of this process is that it should reliably and substantially reduce the number of thermo-tolerant bacteria in water. For the experimental work, the faecal coliform (FC) count will be employed as the primary measure; this will enable reference with the World Health Organisation (WHO) water quality standards. The minimum threshold of satisfactory performance from the filter in terms of reduction in FC count, will be set at a reduction to the WHO 'Low Risk' quality class (0-10 FC/100ml). For rainwater harvesting, input water is unlikely to be more than 20 FC/100ml. However, if the tank is used in the dry season to store pond water or similar, the input FC count could be as high as 300 FC/100ml, or higher depending on the source. The filter should also develop a satisfactory performance within seven days of installation or cleaning.

Equally important is that the process should not substantially increase the cost of the tank, nor reduce storage volume. Arbitrary ceilings of +5% cost and –5% effective volume will be applied, which in a typical rainwater tank limits sand depth to about 100mm. For this reason filter depths of 50mm and 200mm where chosen for the experimental laboratory work.

The filter should not interfere with the operation of the tank, for example by causing a very low output flowrate or by making cleaning much more difficult.

In a gravity flow tank, any slow sand filter will normally be placed at the bottom of the tank, a position that makes its surface vulnerable to blockage by falling sediment. Tolerating, removing or diverting such sediment will be an issue of interest in the design of a successful in-tank filter of this type.

This paper examines the feasibility of using in-tank slow sand filtration in the context of a domestic rural rainwater tank in a developing country (although the application could be far more wide-ranging).

LABORATORY WORK

Slow sand filtration is a long established technique for reducing turbidity and bacteria in water; it has been in large-scale use for 100years. It is known to work through two processes; physical sieving in the body of the sand, and biological predation in the active protozoal slime layer (schmutzdecke) that forms on the surface of the sand. In a conventional slow sand filter, a filter depth in the region of 1m is used and the vertical flowrate is around 200mm/hour. The head driving the flow, overcoming the resistance to laminar flow, may be up to 1.5m, and when the flowrate under this maximum available head drops too low for operational needs, the filter is deemed to need cleaning (scraping or reverse-flushing) or recommissioning.

Within a rainwater tank, the filter will be much shallower than 1m; with +5% cost and –5% effective volume ceilings in a 1.5m diameter, 2m high tank, a sand depth of 10cm may represent all the sand that can be allowed. This equates to 175litres, or 0.175m^3 as the maximum volume of the filter, and 264kg weight of sand, the cost of which will vary worldwide.

The mean flowrate through the filter will be low (assumed to be in the region of 3mm/hour when we consider realistic domestic usage). The flow will also be intermittent (unless we add a receiving jar to accumulate a steadily dripping output), since water is withdrawn from the tank perhaps six times a day, for two minutes each time (or enough to extract sufficient water for a households immediate needs). This uneven flowrate will have an intermittency factor (peak flowrate/ mean flowrate) in excess of 100, since daily withdrawal may occur in under 15minutes.

Slow sand filtration as a system of water purification has been in continuous use since the beginning of the twentieth century and has proved effective under widely differing circumstances. It is simple, inexpensive and reliable, and is still the chosen method of purifying water supplies for some of the major cities of the world. Literature provides a wealth of information regarding deep (greater than 1m depth of filter material) slow sand filters, but very little about shallower filters subject to intermittent flow (e.g. Huisman, 1974; James & Evison, 1979; Tebutt, 1999). Using experimental procedures the performance of such filters will be analysed.

Experiments

A real rainwater tank was simulated by scaling down the flowrate in proportion with the surface area of the filters. This led to areas and flowrates around 1% of those typically found in rainwater stores (0.0088m^2 and 0.44l/day respectively). The test rig was designed to compare the effectiveness of 50mm and 200mm deep filters, with two of each constructed alongside each other. It also contrasts continuous and intermittent flow, with each flow regime passing through each depth of filter. Three parameters were therefore varied; filter depth, intermittency of flow and dirtiness of input water, and the bacterial quality of the outlet was measured.

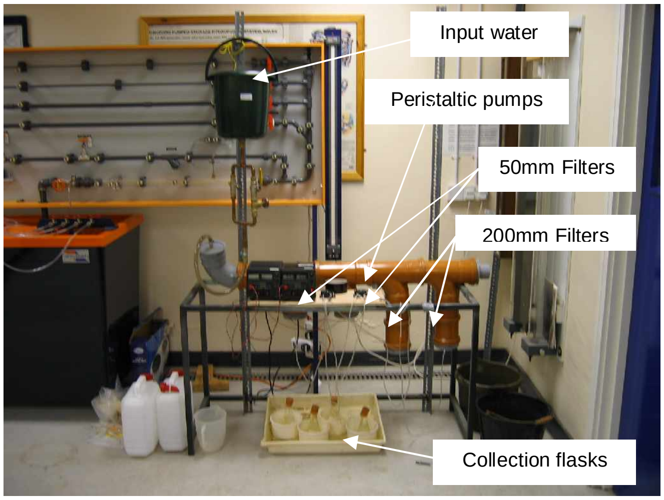
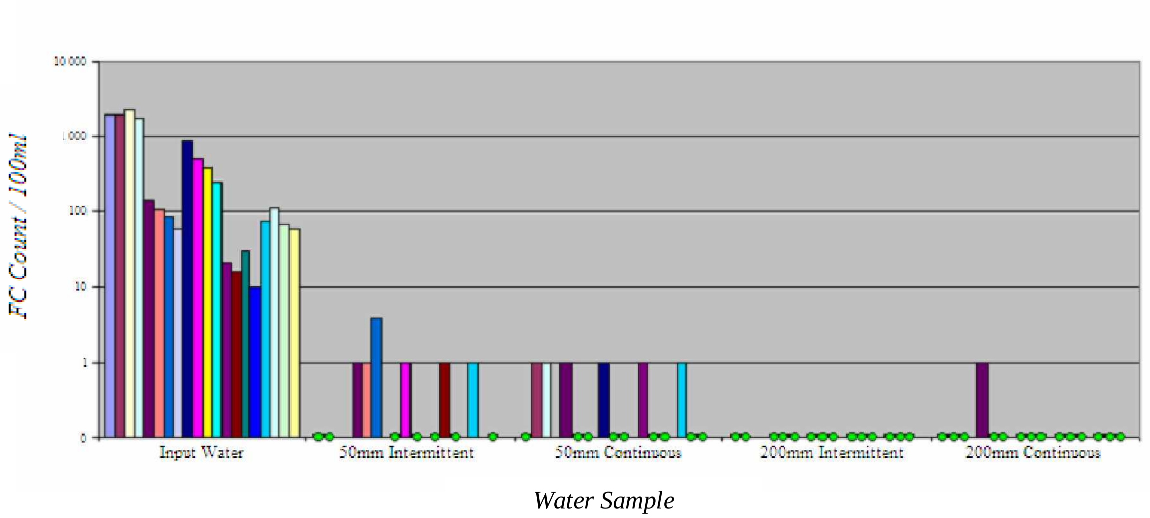


Figure 1 Laboratory Test Rig Set-Up

2.2 Results

Figure 2 Graph of Laboratory Water Quality Tests:



The symbol 🟢 highlights a zero reading. Gaps in the graph result from absence of data.

Table 1 Summary of Laboratory Water Quality Tests:

	Input Water	50mm Intermittent	50mm Continuous	200mm Intermittent	200mm Continuous
Average FC/ 100ml	545	0.6	0.4	0.0	0.1

Comment on Laboratory Work

The results clearly show a massive reduction in FC count across all filters, with little difference in performance between either 50mm and 200mm deep filters or intermittent and continuous flow regimes. The outlet quality is superior to water fetched from protected wells and springs, but not up to Euro/ US piped water standards.

A highly intermittent flow regime gave similar outlet quality to constant flow. The intermittency factor does not seriously affect the performance of a filter, thus this method is suited to the sporadic draw off patterns expected in realistic domestic use.

When the filters dry out, their performance is impaired. This was confirmed by lab findings (comparing to Table 1, the respective values for the filter outputs were 19.0, 17.5, 1.8, 2.6). For good operation it must be ensured that there is always a layer of water above the surface of the filter. This shouldn't be a major concern in a domestic rainwater tank as they are rarely totally empty. If they do become empty, it will not prevent the filter from working, but care should be taken with the water first extracted. One recommendation might be to use supplementary control measures, such as boiling, for the first day or two if very high quality water is needed from the outset. If it is possible, during tank construction, the tap or external off-take could be positioned slightly above the top level of the sand to ensure a minimum water level.

Satisfactory results were found with a filter depth of only 50mm. The implications of this are that the filter surface area could be considerably smaller than the internal diameter of a rainwater tank, or the mean flow rate could be higher, and comparable results could be expected.

At the outset it was decided that the minimum threshold of satisfactory performance from the filter in terms of reduction in FC count, would be a reduction to the low risk WHO quality class (0-10 FC/ 100ml). The results have more than satisfied this, and the fact that the filters reliably reduce the FC count from high risk to low/no risk is very good when considering that the tank can then not only be used for rainwater (which typically has a fairly low FC count) but also as a water storage/ quality improvement system for water from other, more polluted sources such as tube wells or surface watercourses. It was found that the output quality was not a fixed fraction of inlet quality so a 'reduction factor' was not a useful descriptor. Output does not depend on input, and when there was a very dirty input, a reduction of two WHO quality classes could be seen.

Another criteria for viability was that the filter should also develop a satisfactory performance within seven days of installation or cleaning. Experience has shown that after a period of inactivity, the first set of samples taken can be discounted, as they are usually slightly poorer than following results i.e. the filter is 'settling down'. The filters were working at full effectiveness only 24 hours after restarting the rig, well within the seven day limit.

Sedimentation is not a major issue in the test rig although it will prove more relevant in a field situation where roofwater turbidity can occasionally be high and debris from the roof is liable to enter the tank.

FULL-SIZE DESIGN AND TESTING

Full size experiments were undertaken in tanks in Uganda with a view to confirming (or otherwise) the efficacy of the technique. Filters were placed in two positions, one at the bottom of a tank, covering the floor, and another at the top in a separate unit attached to floats so that it draws water from near the surface. Both filters were operated in deliberately unfavourable conditions to ascertain the robustness of the system. Very turbid pond water was used as the input water, and both filters were constructed out of generic, readily available materials.

The ideal situation would be to draw water from high in the tank, where the water quality is best, and then pass through a filter in base of tank. The filter output could be connected to either a tap or hand pump input.

Ordinary builders sand was used as the filter material. This was initially sieved through a 5mm mesh to remove large stones. Wire window mosquito mesh was then used to sieve out 2mm-5mm grains which are used to form the coarse support layer that will surround the drainage hose. The <2mm grains were then sieved through ordinary nylon mosquito netting (as used over beds). This allows separation of 1-2mm grains to make the middle layer, and the <1mm grains make up the active layer. Each grade of sand was thoroughly washed to remove dust and organic matter that would otherwise clog up the filter or contaminate it.

3.1 Tank Floor Filter

A hot knife was used to make slashes in PVC hose, knotted at one end, that is connected to the outflow pipe within the tank. This was arranged in a loop on the (round) tank floor to provide even distribution of drainage.

Figure 3 Drainage hose arrangement

Figure 4 Coarse layer distribution

A 100mm depth of water was poured into the tank, and then the coarse layer was carefully poured over and around the hose to a depth of 15mm. The middle layer of sand was poured in the same way, facilitated by standing in the centre of the tank and pouring in an even circle over the hose and coarse layer. This was done to a depth of 10mm. The active layer was distributed over the entire bottom surface by sprinkling the sand into the water from outside the tank.

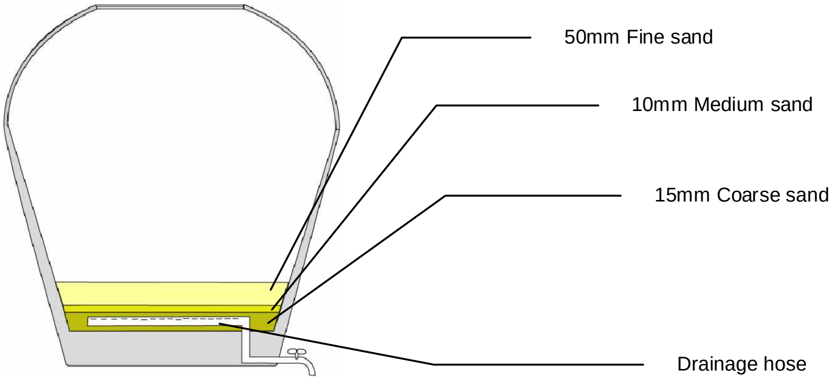


Figure 5 Schematic of Floor Filter

Jerry cans of water from a nearby pond water source were added to the tank as the rainwater available to use proved to be too good, with an excellent bacteriological quality of 0 FC/100ml. Ordinarily this would not be an issue and the filter could be left alone, but to accelerate the growth of the schmutzdecke, pond water was used which had an FC count of 250 FC/100ml. It was, unfortunately, very turbid (50TU) which could affect the performance of the filter. It also impeded the bacteria counting procedure by constraining the size of the water sample that could be tested. A diffuser plate was made of strips of scrap tarpaulin to diffuse the flow of water into the tank to prevent the inflow disturbing the sand layers.

3.2 Floating Tank Filter

A self contained unit filter was also constructed, initially out of concrete, but to reduce material cost and for convenience, a 10 litre plastic bucket was used in testing. Into the base of this was a plug covered with fine wire mesh, to which a hose was attached. 10mm of 2-5mm grains was put over the mesh, and then ordinary builders sand with >2mm particles removed was washed and used as the active layer, to a depth of 50mm. The bucket was then topped up with water and empty plastic bottles were tied onto the outside using a bicycle inner-tube. It was then floated in the tank, as shown in Figure 7. The lid was loosely attached to allow water to enter, but prevent detritus entry. The outlet hose was brought through the top of the tank and siphoned to initiate water flow. This was to simulate a situation where the filter would be used in a tank that already has water in it. In such a scenario it would be difficult to connect the outlet to the fitting in the base of the tank.

The two designs are illustrated below:

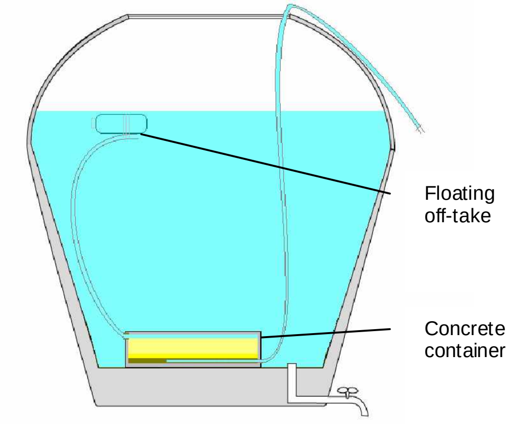


Figure 6 Schematic of Concrete Filter

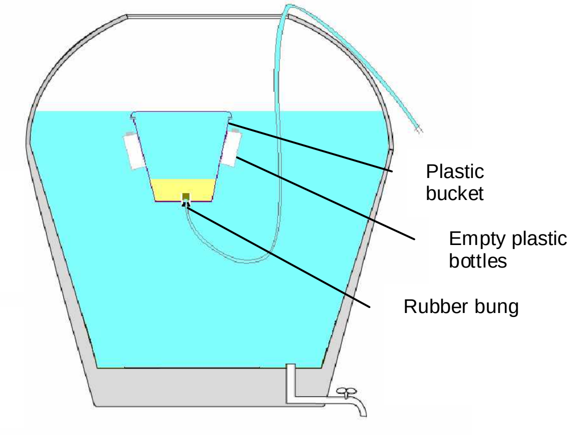
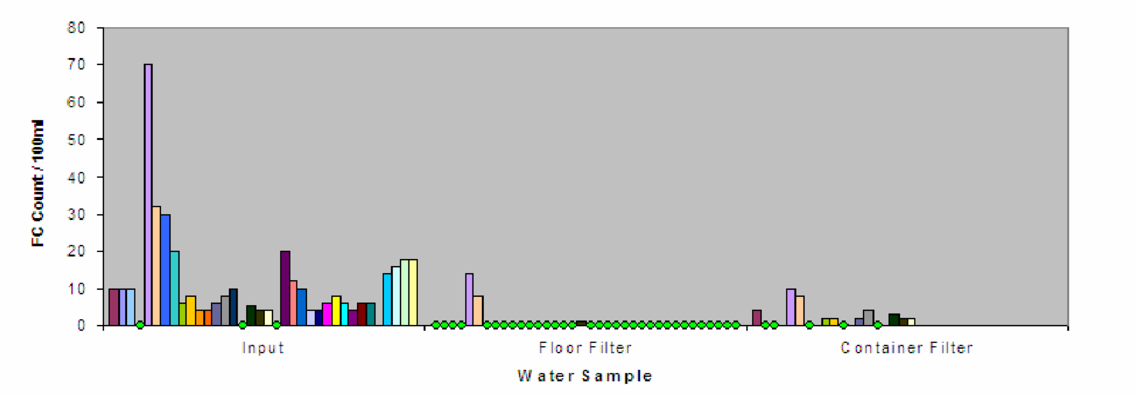


Figure 7 Schematic of Floating Filter

Comment on Full Size Design and Testing

Figure 9 Graph of Full Size Water Quality Tests



The symbol ● highlights a zero reading.

Table 2 Summary of Full Size Water Quality Tests

	Input	Floor Filter	Floating Filter
Average FC/ 100ml	11	1	2

The data shows that both filters reduced the outlet FC quality to less than 2 FC/100ml (WHO low risk) even under extreme conditions. The filter designs are vulnerable to high turbidity, and yet low-turbidity high-contamination water was not available in the rural Ugandan environment where testing was done.

The construction of the floor filter posed no major problems, and performed well considering the shallowness of the active layer and the high turbidity of the input water. The maintenance of such a filter would consist of stirring the top layer of sand with a stick and scooping out the resultant floating debris and dirty water. It is anticipated this would have to be done no more than every two or three months.

The container filter is only suited to batch production out of concrete, as material cost makes it unviable for an individual household to make just one. The floating container construction which used a plastic bucket (which would be more accessible to a household) proved problematic as the bottom hose became disconnected, giving false readings, and efforts to repair it meant the filter would have to be re-laid, upsetting the existing schmutzdecke. Unfortunately time ran out and this work was unable to be completed. However, if a method of reliably connecting hose (or similar) to standard plastic buckets could be established, the initial results certainly warrant further wok in this area.

Increasing the filter depth to 100mm could also be beneficial to the performance of both filter designs without affecting material volume or cost too greatly.

Conclusions

The very positive laboratory results certainly warrant further work into physical representation of the filter and system design. Indeed this is fundamental to making these very positive experimental results useful in a wider context. Filter size, construction and cost will all be crucial factors in making in-tank slow sand filtration (SSF) a viable option for improving domestic rainwater quality. Work could also be done into filter material possibilities where graded sand is not an option. Investigation into other filter materials would include materials such as un-graded sand, rice husks or crushed coral which are known to be used as filter material around the world where graded sand is not available. Practical tests in the field have made progress in this direction but the impact of factors such as heat, quality of filter material, and daily patterns of usage and demand on filter performance need to be explored.

In-tank SSF is a feasible option with affordable (very shallow) filters, and has other attractive user properties. It is tolerant of the high intermittency inherent in the outflow of a domestic rainwater harvesting tank, and under some conditions gives excellent water quality. Laboratory work showed that with rainwater as the input water, excellent quality could be achieved. Field work showed that with very turbid pond water there are good improvements in water quality. This is particularly interesting when considering the use of rainwater tanks to improve the quality of water available in the dry season. In this context the tank can be used as a storage and quality improvement facility for any given water source.

Figure 10 Turbidity reduction in floor filter, input shown on left, output on right.

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[i] Pacey A. & Cullis A., Rainwater Harvesting; The Collection of Rainfall and Runoff in Rural Areas, Intermediate Technology Publications, 1986