Interim Design, Construction and Operation Guidelines for a Biologically-Enhanced Iron Removal Filter for Attachment to Handpumps

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1. Introduction

1.1 The iron problem

Groundwater is a favoured source of potable water supplies in rural areas in developing countries because it is generally regarded as unpolluted and can be safely consumed without the need for treatment. In many rural conditions simple well-handpump systems are used to abstract and supply the water. In such circumstances treatment is avoided wherever possible because of the practicalities and costs involved. However groundwaters may have other properties which can indirectly affect health and water use. Iron in rural groundwater supplies is a common problem (concentration range: 0 to 50 mg/l - WHO recommended <0.3 mg/l). The iron occurs naturally in the aquifer but levels in the groundwater can be increased by dissolution of ferrous borehole and handpump components. Iron-bearing groundwaters are often noticeably orange in colour, causing discoloration of laundry, and have an unpleasant taste which is apparent in drinking and food preparation. People are put off such groundwater supplies and resort to the traditional, polluted surface water sources.

1.2 The purpose of this document

A handpump-attached iron removal filter has been under development since 1995 at Cranfield University at Silsoe, UK. This research was supported by the Engineering Division of the Overseas Development Administration (now the Department for International Development [DFID]). Experimental filters were designed and tested in the UK and a prototype filter constructed and tested in Uganda, with the support of Mott McDonald Ltd. and the Ugandan Department for Water Development.

The purpose of this document is to:

- report the principal findings of the research;
- translate the findings into practical guidelines for design, construction and operation and;

- to identify areas of uncertainty which require further work.

There is sufficient evidence to suggest that the goal of developing a simple, effective handpump-attached iron removal filter is achievable. The authors of this report believe, however, that the production of a robust, sustainable and user-friendly version of the experimental filter requires further work. Consequently, this is not intended to be a definitive design, construction and operation manual for use in the field. Instead, we hope that individuals and organisations, who are in the business of evaluating such new technologies and who have an interest in iron removal, will put our advice into practice and report back on their experiences so that there is a process of continuing improvement.

2. The process of biologically-enhanced iron removal

2.1 Chemical iron removal

Conventionally, iron is removed from groundwater by creating a strongly oxidising environment. This is usually achieved by aeration; by the addition of oxidants such as chlorine or by raising the pH of the water using alkaline materials such as limestone. Under such conditions, soluble ferrous iron is oxidised to ferric iron which subsequently forms a precipitate of insoluble iron hydroxide which may then be removed by filtration. This technology has been successfully adopted to treat groundwaters around the world for many decades.

2.2 Biological iron removal

In the past ten years, biological iron removal filters have been promoted as an alternative to the traditional chemical approach. Microbiologists have known for many years that certain bacteria are capable of oxidising and immobilising iron. The bacteria responsible for the process appear to be natural inhabitants of the well environment and therefore, the microorganisms necessary to initiate the process are carried with the groundwater on to the filters. The active population of iron-oxidisers, which requires aeration in order to stimulate its growth, grows on the surface of the filter bed in the form of a slimy orange mat. It is within this zone of bacterial activity that the iron removal process appears to occur. Proponents of biological iron removal claim that this biologically-enhanced process is more efficient than the chemical process.

2.3 How to ensure that your iron removal filter is “biologically-enhanced”

There is some debate about the categorisation of iron removal systems as “chemical” or Technologies which involve the addition of chemical oxidising agents such as chlorine are clearly designed to promote a chemical process and are likely to inhibit bacterial activity. However, the majority of earlier handpump-attached filter designs rely simply upon aeration to promote chemical oxidation and precipitation, a feature that is common to our biologically-enhanced version. Evidence suggests that iron bacteria are ubiquitous and that significant populations exist in many well environments where iron-containing groundwater is being abstracted. Therefore, it is probable that earlier chemical iron removal filters were in fact biologically-enhanced. Similarly, it is quite likely that chemical oxidation plays a role in a biological system. This sometimes leads to confusion amongst academics over how the new biologically-enhanced system differs from what has gone before.

The practitioner is usually not concerned with such academic debate. The purpose of this research was to incorporate the process of biological iron removal into a handpump-attached system which is sustainable at the village level in developing countries rather than to investigate the iron removal process *per se*.

3. Design criteria and philosophy

3.1 Existing experience

Incorporating the process of biological iron removal into a handpump-attached system which is sustainable at the village level in developing countries is easier said than done. A number of iron removal filters have been designed for use in association with handpumps in recent years (Chibi, 1991; Ahmed and Smith, 1987; Patnaik, 1987; Padmasiri and Attanayake, 1991; DPHE/UNICEF, 1988; WaterAid, [undated]; ECOVIC/UNICEF, 1994). These systems have met with mixed success. On the positive side, it is clear that small-scale systems can remove iron effectively - whether it be a chemical and/or biological process which predominates. In addition, it has been shown that small-scale systems may be produced at an affordable cost and implemented at the village level. However, concerns remain regarding the sustainability and user acceptability of such systems.

The design criteria and philosophy which we believe are fundamental to the development of a successful handpump-attached iron filter are set out in the following paragraphs.

3.2 Simplicity and robustness of design

The design must be sufficiently simple to allow a flexible approach to manufacture. By keeping the design simple, it should be possible to manufacture filters, affordably, either in small numbers at the village level or in larger numbers by an industrial manufacturer. Although a simple design is important, like a handpump, the filter must be manufactured to a high quality to ensure robustness.

3.3 Retrofitting

The filter should be retrofittable to existing handpumps with the minimum of modifications to the handpump or to the apron.

3.4 Flow of filtered water

The filter should produce water at a rate similar to that produced by the pump. Handpump flow rates normally vary in the range 0.2-0.3 l/s (if well installed and maintained). Failure to produce filtered water at such a rate is likely to annoy the user and lead to queuing. In addition, users will expect water to emerge from the filter immediately after pumping commences. Again, failure to produce clean water rapidly is likely to lead to queuing and irritation. We propose that there should be less than a 50% increase in the time taken to fill a jerrycan.

3.5 Outlet height

Water should exit the filter at a height which permits its collection in a 0.45 m high jerrycan - a very widely used collection vessel worldwide.

3.6 Water quality

The WHO recommend that drinking water should have an iron concentration of no more than 0.3 mg/l.

3.7 Filter cleaning

It should be possible for one person to clean the filter in less than an hour on a weekly basis after a limited amount of training.

3.8 User know-how

The filter should require no operational skills on the part of the user other than knowing where the outlet is.

4. Principal Findings

4.1 Description of the system

A very simple downflow filter design has been developed, with the aim of making it affordable to build, simple to operate, and less likely to break down.

The key components of the filter are outlined in Diagram 1. Water from the handpump enters the filter and is directed onto an aeration tray. Water droplets fall from the aeration tray onto a few millimetres of standing water before infiltrating into the filter sand. A slotted drainpipe, set into a thin gravel blanket, collects the filtered water which exits via an outlet at a height of 0.45 m.

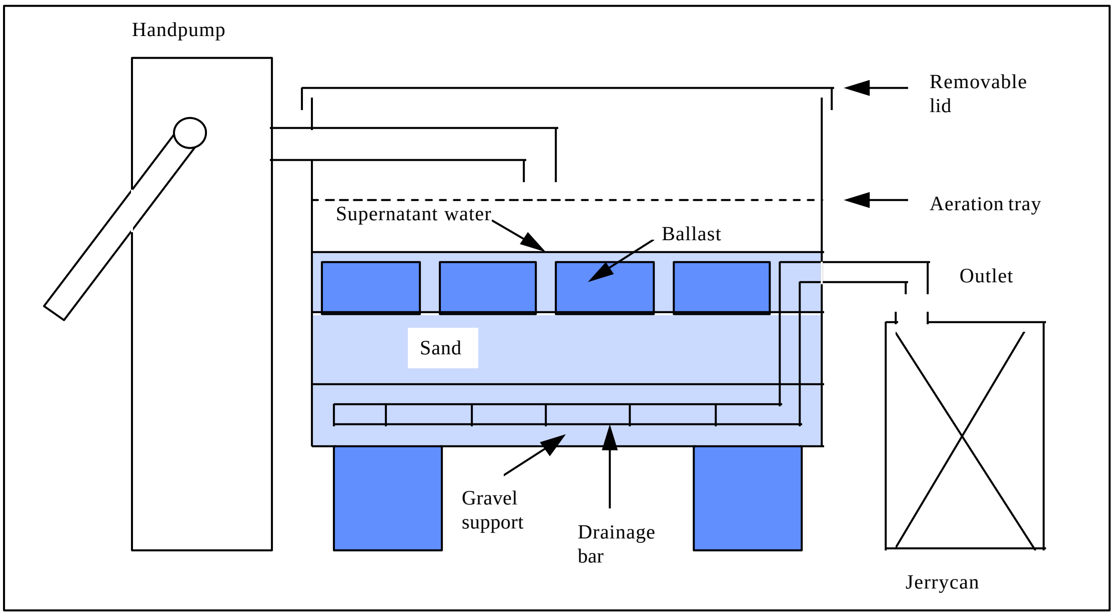

Diagram 1 Sketch diagram of the iron removal filter

4.2 *Surface area requirement*

Experimental work at Silsoe, backed up by field testing in Uganda, suggests that a filter of approximately 1 m^2 surface area is necessary to deliver filtered water at a rate of about 0.25 l/s (assuming that guidelines on head and filter sand size / depth are followed).

4.3 *Sand depth and size*

A sand bed depth of 0.15 m is capable of consistently reducing iron concentrations of about 7 mg/l to <0.3 mg/l. Such consistent performance is achievable with a sand of 1.18 mm effective size. This sand needs a 0.05 m deep gravel support layer to ensure that it does not escape through the hacksaw cut slots in the drainage bar.

4.4 *Head requirements and the need for ballast*

The head needed to deliver an acceptable flow rate of 0.2-0.3 l/s in unclogged sand is 50 mm. This will increase as the filter clogs. To raise the water level from the top of the sand to a height of 50 mm requires 50 l of water to be pumped (assuming 1 m^2 surface area), and therefore it would take 3 minutes of pumping just to reach the desired flow rate. This delay may be largely overcome by adding ballast to the filter. In our Ugandan trial water-filled plastic bags were used as ballast. This approach worked well, taking only 29% more time to fill a jerrycan from the filter than it took directly from the handpump. **It may be possible to improve this performance but further work is needed to assess the effect of ballast on the iron removal process.**

4.5 *Aeration*

The water entering the filter must contain some oxygen in order to promote the oxidation of iron. **Do some checks on the DO from the handpump itself.** The water only needs to reach about 40-50% oxygen saturation and this may be achieved due to the aeration that naturally occurs in the handpump spout plus that provided by a perforated aeration plate.

4.6 Clogging and cleaning

Iron filters become clogged over time due to the accumulation of iron precipitates, bacterial slime and trapped gases. In order to maintain an acceptable flow rate through the filter, it must be cleaned periodically. If it is cleaned too often, the filter bacteria become destabilised and iron removal performance deteriorates. If the filter is not cleaned frequently enough, the time taken to deliver a given volume of water will increase to an unacceptable level. The human aspect of filter cleaning is also important. If cleaning is arduous and has to be carried out very frequently then it is less likely to be done.

Although many cleaning techniques were tried, the most convenient (to the research staff) was a combination of stirring and bailing carried out on a weekly basis. The sand is stirred gently with a stick and in doing so, iron deposits and entrapped gases are released. The iron deposits tend to float up from the filter sand and are dispersed in the supernatant water. They can be removed from the filter by bailing with a small bucket.

5. Proposed Modifications to be Incorporated into the Design of the Mark II Filter

5.1 Vertical dimensions

The experimental and prototype filters built to date have been designed to discharge filtered water at an outlet height of 0.25 m i.e. the height of a medium-sized bucket. The field-testing exercise in Uganda demonstrated that this outlet height was, in the majority of cases, too low and that the aim must be to discharge filtered water into a 0.45 m high jerrycan - the standard collection vessel. In order to deliver water at this height, the vertical dimensions of the filter become crucial and, we believe, a minor modifications to the filter and, perhaps more controversially, to the handpump are necessary. The vertical dimensioning necessary to accommodate a jerrycan beneath the outlet spout of a U2 pump (a clone of the standard Afridev pump produced by Victoria Pumps, Kampala, Uganda) is shown in Diagram 2.

The U2 pump outlet is normally at a height of 505 mm above the surface of the handpump apron. By adding a 105 mm spacer between the handpump stand and the water tank assembly, the invert of the handpump spout will be at 610 mm. By minimising the space given over to aeration and raising the filter up on a brick support, we believe that a jerrycan can be positioned beneath the outlet pipe. Experimental evidence suggests that 50 mm of head results in >0.2 l/s discharge in clean sand.

5.2 Towards a robust, sustainable design

A number of experimental and prototype filters have been built so far. The experience in Uganda, in particular, highlighted the degree of filter component robustness needed to ensure sustainability. Like any structure designed to be used on a daily basis by members of the public, normal use and occasional misuse requires considerable attention to detail in terms of design and particularly materials choice. A number of components of the

Ugandan prototype (the lid, the connection between the handpump spout and the filter, the outlet pipe and the drain plug) were insufficiently robust to survive more than a few weeks. These issues require systematic evaluation and modification in the next phase of research. As ballast will be an essential component of any future iron filter of this type, its design and materials choice will require particular attention.

6. Operation and Maintenance

6.1 Start-up

Because microorganisms play a part in the process, iron removal does not occur at its maximum rate immediately following the installation of a new filter. There is a start-up period of around 10-15 days during which time an active population of iron bacteria builds up in the filter. Iron bacteria are ubiquitous in the groundwater environment and therefore, as soon as the filter begins to receive groundwater, it will become colonised by these organisms.

n.b. the iron bacteria responsible for the treatment process are harmless to humans.

6.2 Clogging

Over a period of days, iron/bacterial deposits, which have a distinctive orange/brown colour and slimy appearance, accumulate on and within the sand bed. These deposits clog the sand filter and impede the flow of water, requiring a greater head of water to deliver an acceptable flow rate and therefore increasing the pumping time needed to deliver a full jerrycan. Flow through the filter is also affected by the accumulation of gases within the bed. To reduce clogging and associated delays, the filter must be cleaned on a regular basis.

6.3 Cleaning

6.3.1 How is the filter cleaned?

To reduce clogging it is necessary to dislodge the iron/bacterial deposits from the sand and remove them. This can be achieved by stirring the sand gently with a dedicated stirring stick. By stirring, the sand is disturbed and the iron deposits are dispersed into the supernatant water which will immediately become discoloured. If this dislodged material is not removed, it will settle back down onto the surface of the sand and therefore it is necessary to remove it by bailing with a small bucket. The wastewater can be disposed of by pouring it into the handpump apron soakaway. Stirring also effectively dislodges gas bubbles which emerge through the supernatant water and escape to the atmosphere. A detailed cleaning protocol is set out in section 6.3.3.

6.3.2 How often should the filter be cleaned?

The experimental work suggested that the most effective approach was to clean on a weekly basis for approximately one hour at a time. Weekly cleaning ensures that clogging deposits do not build up to levels that will cause unacceptable delays to users.

Limiting cleaning to 1 hour per week, should not cause too much inconvenience for users. Cleaning also has a deleterious effect upon the iron concentration as disruption of the sand bed and the iron bacteria within it reduces the efficiency of the filter. It may take a few hours to return to the pre-clean level of iron removal. Therefore, if the filter is cleaned more often than once a week, it will not have the opportunity to establish a steady state condition.

The exact cleaning interval and duration of cleaning should be determined by the users at each site. The amount of iron that will be removed per week and the amount of gas bubbles produced will vary from place to place. Thus, the cleaning regime should adapt to reflect this variation. There may be sense in cleaning the filter at night when handpump usage rates are likely to be low and the biofilm would have several hours to recover from the disturbance before the filter is likely to be used again.

6.3.3 Suggested filter cleaning protocol

- Unlock and remove the filter lid
- Cap the outlet pipe
- Stack the ballast so that half of the filter sand surface is exposed
- Pump water into the filter until the water level reaches the outlet pipe
- Stir the filter sand with a stirring stick for about two minutes. A stick the size of a standard broom handle is ideal. It should be marked to tell the user how far to insert the stick into the sand. As the filter sand is underlain by a gravel support layer it is sensible to avoid mixing. The Ugandan cleaning stick was marked at 26 cm (16 cm of water between top of sand and overflow invert + 10 cm of sand leaving a 5 cm margin of safety). The user will see gas bubbles rising from the stirred sand and large amounts of iron which will make the supernatant water very cloudy.
- The iron-rich supernatant water should then be bailed out with a bucket and the wastewater disposed of via the apron drain and soakaway. It is acceptable to leave about 50 mm of standing water on the surface of the sand as attempts to remove this may lead to sand being inadvertently lost from the filter.
- Replace the ballast and replace the filter lid.
- Uncap the outlet and pump until the filtered water comes clear (this may take a few minutes).

The following equipment is needed for cleaning:

- A cap or bung for the outlet pipe
- A marked stirring stick
- A bailing bucket

These items and their hygienic storage, should be the responsibility of a filter caretaker (see section 7.4).

7. User Motivation and Management of the Filter

7.1 Prerequisites for success

For the system to be successful, three inter-related factors must be addressed:

- motivation,
- maintenance system,
- coverage of costs.

The following sections address these issues.

7.2 User interest - is iron really a problem?

The success of a small-scale, village-level water treatment system is highly dependent upon the level of user interest. The attachment of a filter onto a handpump will, inevitably, make it less convenient to use. There will be a delay before water starts to emerge from the handpump at an acceptable rate. When the filter starts to clog, that delay will increase. Every week, the filter needs to be cleaned. Somebody needs to do this job and they will need an incentive to encourage them. Why would people be interested in this system?

If the handpump significantly reduces the distance to be walked to a traditional water source, but the users are put off by the taste and colour, then there may be sufficient interest in a water treatment system.

If the handpump has been installed to provide water of improved microbiological quality but water from traditional, iron-free, sources is readily available then considerable effort will need to go into educating users of the health benefits that can be derived from drinking the microbiologically safer handpump water and, in the process, paying for the installation and/or management of an iron removal filter.

One additional possibility should be considered before embarking on the construction of an iron removal filter. Perhaps iron is not a problem at all. That a handpump is not being used and the groundwater it delivers contains iron are not necessarily linked. It is possible that other factors are limiting interest in the handpump. Perhaps the pump does not work very well. Perhaps it is inappropriately sited. Perhaps there is something else about the water quality that people are not used to (salinity, temperature, sulphide).

7.3 User training

The ideal situation would be one in which the user requires no training, i.e. the filter simply becomes an extension of the handpump and requires no additional user knowledge. If the filter cannot be made to operate without significant user understanding it is likely to fail.

7.4 Filter maintenance - the need for a caretaker

As regular cleaning is a prerequisite for the sustainable operation of an iron removal filter, it is considered vital that the system has a part-time caretaker appointed. Random cleaning by users is likely to lead to destabilisation of the iron bacteria and inconsistent iron removal. A caretaker would be able to get to know the pattern of clogging and the interval/duration of cleaning required to restore flow to an acceptable level. This person could also look after the cleaning equipment.

7.5 Costs

The prototype built in Uganda cost about £235 of which £200 was the cost of the tank (which could be made more cheaply). The principal recurrent cost would be the employment of a caretaker. Even if a donor is prepared to pay for the filter itself, it may be that the community have to pay the caretaker's wages. This is another example of where user motivation is important. Perhaps the caretaker could have a combined role for the upkeep of both the handpump and the filter. Such an arrangement would depend on how water supply is organised at a given location. The caretaker is likely to need additional, occasional support in the event of more serious problems with the operation and maintenance of the system.

8. Production options

8.1 Introduction

The ODA research project focused on proving the filter performance, against a background of general handpump constraints (e.g. spout height, assumed collection container height, handpump discharge). All testing was carried out on laboratory rigs at Cranfield University in the UK. Before the completion of the ODA project, the Lyantonde prototype was set up and tested in September 1996. As a consequence of the work described in the present report, it is anticipated that a Mark II filter will be designed and fabricated in UK. The iron removal filter will thus have gone through three stages: laboratory rigs, the Lyantonde prototype and the Mark II design. In considering the long term future of the filter, several options arise. These are outlined in the following subsections.

8.2 UK commercial manufacture

A UK manufacturer of handpumps, small water treatment systems, or similar could be invited to adopt the Mark II design. The advantage of such an approach would be the achievement of high quality of manufacture. It is likely however that such an option would result in high costs, particularly when freight and importation charges are taken into account.

8.3 Local commercial manufacture

A Ugandan manufacturer could be provided with detailed drawings / specifications, and invited to produce the filter commercially in-country. Although this would result in a lower cost product, the quality of the result, at least initially, is likely to be poorer than the first option. In the long term however, this option is very attractive, especially if a local organisation can be found to supervise the initial manufacture, and provide quality control.

8.4 Public domain design

The third option is to publish the design drawings and technical specifications, with a view to fabrication by individuals, non-government organisations, or the private sector. Such an approach, which was pursued by UNICEF with the India Mark II handpump, and more recently by SKAT with the Afridev, has the potential to develop more market competition, but it would also result in variable quality of product.

8.5 Kit supply

The fourth option is to supply a kit comprising the necessary fittings for inclusion in a masonry or ferrocement tank constructed in situ. This would have the advantage that the key parts would be of good quality but overall costs would be reduced through use of local materials.

None of the four outlined options is without drawbacks, and it may be that promotion of all four would lead most quickly to the wide availability of a product of adequate quality at sufficient low cost.

9. Feedback

If you have any comments on this manual; require additional advice; or wish to feedback your own experiences of iron removal filter design and operation, please contact:

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