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Family scale rural water treatment plant: intermittent slow sand filtration

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erythrocytes in blood and impedes the transmission of oxygen.

In practice the main cause for concern is faecal pollution of water sources which causes chronic diarrhoea, especially amongst infants. In a research study conducted in the Ditsobotla district in Bophutatswana, South Africa, (van As & Kasbergen, 1984) 49% of children under the age of six suffered from diarrhoea at least once a year. The mortality rate for under five year olds is 10.5%, of which 22% resulted from diarrhoea.

3.5 Determining water quality

Determining water quality is a subjective exercise for most rural people when assessment is based on sensory perception. The main criteria are taste, smell, clarity and color. In many areas factors such as bacteriological quality are not considered. It would, however, be incorrect to assume that all communities are ignorant of the fact that some water, although appearing palatable, is 'bad' and is detrimental to health. (Faniran, 1986)

A number of factors need to be considered when determining water quality:-

Temperature

pH (usually between 6 and 8 for natural water)

Conductivity, which gives an indication of total dissolved solids (TDS).

Turbidity, which indicates the clarity of the water.

Bacteria contamination, which is indicated by the total plate count test and recorded as total bacteria per ml.

Faecal contamination, which is indicated as either total faecal coliform or E-coli Type I and recorded as counts per 100ml.

A total chemical analysis of the water is important if either chemical contaminants or deficiencies are expected or if the total dissolved solids is high. Records available from other sources will give an indication of the chemical constituents in the water in a region but often large variations can be expected within an area.

The total plate count test gives an indication of the bacteriological purity of the water and the presence of pollutants. "Clean" water will yield about 100 counts per ml, while contaminated water may have several hundred thousand counts per ml.

Pathogenic organisms are difficult to isolate but they coexist with coliform bacteria which can be isolated and counted relatively easily. Coliform bacteria are normally found in the intestinal tract and are more resilient than other pathogens when discharged into water. They do not themselves constitute a threat to health but indicate the possible presence of pathogens and the recent contamination of the water by excreta, which make it unsafe for consumption.

A number of methods exist for determining the level of bacterial infection of water, but the simplest method is the micro-filtration technique. This involves filtering the water through filter paper which has very fine pores through which bacteria cannot pass. The filter is then placed on a culture medium and incubated at specific temperatures for predetermined times. Colonies develop from each original bacteria which are counted at the end of the incubation period.

4. SLOW SAND FILTRATION

4.1 History

The first slow sand Filters were designed in 1829 by James Simpson for the Chelsey Water Company in London (Huisman, 1978). The objective was to clarify river water and the application was so successful that the filters were used elsewhere. The effectiveness of SSF in the removal of disease causing agents was only discovered around 1850 when it was found that water was the main carrier of Asiatic cholera and that it could be effectively treated with SSF.

Until 1920 SSF was the only method used to treat surface waters for public consumption. After the first world war, chlorine came to be used as a disinfectant capable of killing all pathogens and SSF gave way to more sophisticated water treatment methods. However, during recent decades SSF has been reassessed as an effective treatment method in third world applications.

Slow sand filtration requires a large amount of land which is relatively cheap in third world situations. It is inexpensive to construct, does not require the use of expensive unit process equipment, and is simple to operate. SSF does not rely for its effectiveness on the use of chemicals which often cannot be reliably supplied to remote areas.

4.2 Physical processes

The physical processes by which suspended material is removed from the influent water are complex and inter-related (Corbetis, 1984; Huisman, 1978). They include

more than simply a straining action as indicated by the fact that particles much finer than the mean pore size are trapped by the filter. The various transport mechanisms by which suspended particles are brought into contact with the sand grains are discussed below. In most cases molecular forces come into play causing adsorption of suspended particles to the sand, once contact has been made.

4.2.1 Straining

This is the most simple of the filtration processes by which only particles which are too large to pass through the pores are trapped.

4.2.2 Interception

Particles which remain in stream lines (which diverge to pass round a sand grain) but whose radii are greater than the distance between the streamline and the sand grain, will make contact with the surface of the grain.

4.2.3 Inertia

Suspended particles which follow streamlines have inertia which is a function of the dynamic viscosity of the fluid and the specific gravity, radius and velocity of the particle. This inertia causes the particle to maintain a trajectory which is divergent from the streamline and may cause the particle to make contact with a filter grain.

4.2.4 Sedimentation

This is a significant process, especially in highly turbid waters. When particles have a higher density

than water, they are deflected from stream lines under the influence of gravity and may make contact with filter grains.

4.2.5 Diffusion

Thermal molecular energy of the water causes small particles to move in a random fashion as a consequence of transferred kinetic energy. The amount of movement depends on the viscous drag of the fluid and the size of the particle. If the particle is less than 1um in diameter, the movement outside the streamline may be considerable and the particle may make contact with a grain surface.

4.2.6 Hydrodynamic forces

The flow in the filter bed is laminar. This creates a velocity gradient and shear field as a result of which suspended particles spin and move across the streamlines. If the particle has an irregular shape the resultant motion may be random. This effect is increased with the velocity of the flow through the filter but with slow sand filtration and ultra-slow sand filtration, its effect would be reduced.

4.2.7 Flocculation

Particles with opposite net electrical charges attract each other. During filtration this may occur as a result of attraction between suspended material and the sand grains or material already coating the sand grains. This is an electro-kinetic phenomenon.

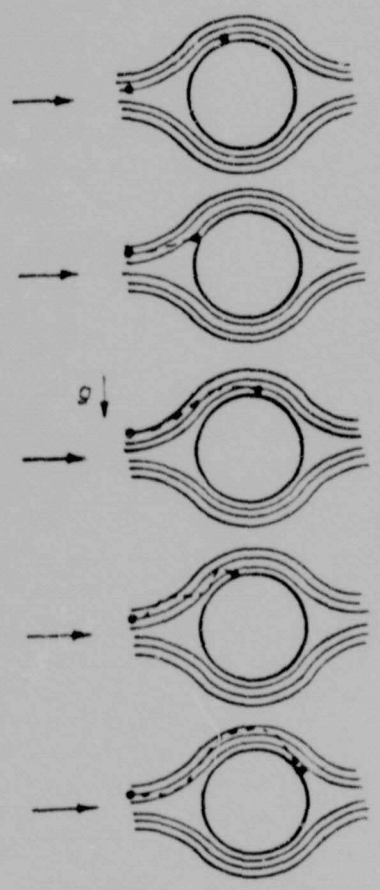


Fig. 4.1 Physical filtration mechanisms

4.2.8 Filter blocking

Suspended material which is trapped by the filter is contained in the pores between sand grains. This blocks the filter as resistance to through-flow increases. In slow sand filtration the blocking is related to the following factors:

the turbidity of the raw water,
the rate of flow,
the filter grain size and shape uniformity.

The filter blocking occurs in the top layer of the filter. The depth of blocking varies from 10mm to 30mm depending on filter grain size, with the lesser depth being found in fine, well graded, sand (effective size, ES (d_{10}) = 0.2mm and uniformity coefficient, UC (d_{60}/d_{10}) = 2). The greatest penetration depth occurs in unsieved coarse river sands with ES = 0.32, and UC = 4). (Paramasivam & Sundaresan, 1979)

It is to be expected that filter runs will be short with high turbidity water, the as the filter traps the suspended matter. For this reason pretreatment is often used to remove the bulk of the turbidity from the raw water. This may take the form of sedimentation or horizontal roughing filters (Wegelin 1984).

The rate of flow affects the filter run length because, for a water of a given turbidity, the greater the flow rate the greater the suspended load extracted by the filter over a given period of time.

4.2.9 Filter head loss

The energy required to pass water through the filter bed may be measured by the head loss through the filter. As the filter traps suspended material, the porosity of the top few millimeters is reduced and resistance to flow is increased, requiring an increasing head loss to maintain the same flow. The resistance to flow may be predicted by the Kozeny-Carmen equation (4.1) which is derived from Darcy's equation of flow in porous media. (Clark, Viesman & Hammer,1965; Corbetis, 1984)

$$\frac{H}{L} = \frac{E(1-f)}{f^n} \bullet \frac{V^2}{g d \Psi} \qquad \ldots\ldots\ldots (4.1)$$

where H : head loss
L : depth of layer
f : porosity
Ψ : particle shape factor
d : grain diameter

$$E = \left[\frac{(1-f)}{R} \bullet 150 \right] + 1.75$$

R : Reynold's number
n : 3

The particle shape factor in the above equation is the ratio of the surface area of the equivalent volume sphere to the actual area of the particle :-

$$\Psi = \frac{Ao}{A} \qquad \ldots\ldots\ldots (4.2)$$

where Ao : surface area of a sphere of volume V

hence $d = \frac{6V}{A\Psi}$

Thus equation 4.1 may be written as

$$\frac{H}{L} = \frac{E(1-f)}{-f^n} \quad \frac{v^2}{g} \bullet \frac{A\Psi}{6V} \qquad \ldots\ldots (4.3)$$

Note that the porosity of the top layer is reduced with time and that graded filter layers must be considered individually.

4.2.10 Primary sedimentation

Primary sedimentation is a process often used in water treatment as a form of pretreatment. The sophistication of the sedimentation process ranges from a simple settlement tank, which is occasionally hand cleaned, to mechanically laundered tanks using complex machinery requiring highly trained operating staff.

Primary sedimentation is used for two reasons -

- to reduce the suspended load of the raw water before it gets to the filters, thus ensuring less filter blocking and longer runs,

- to reduce the "live" loading on the filters of bacteria, and other aquatic life. Waksmann and Vartiovaara (1938) demonstrated that marine organisms may be strongly adsorbed by marine muds, and Weiss (1951) carried out extensive investigations on bacterial adsorption by river and estuarine silts. Both reported E. Coli removals of > 50%. Work done by Milne, Curran, and Wilson (1986) in estuarine waters has shown that the rate of deposition of faecal coliform is proportional to the Suspended Solid concentration and that up to 50% removal of bacteria can be achieved by sedimentation.

4.3 Biological processes

There is not a great deal of detailed information in the literature on the biological processes which occur in slow sand filtration. The biological process is however the most important action of the filter and a description is needed.

On the surface of the filter there exists a layer, commonly called the "schmutzdecke", in which a variety of micro-biological life abounds. This layer has the appearance of a brown slimy mat which is easily disturbed by turbulence. The layer usually contains algae and is the living environment for various forms of aquatic life including plankton, diatoms, protozoa, rotifers and bacteria. The bacteria and organic matter suspended in the incoming water is entrapped in the upper layers of the filter where it provides the food and nutrients for the organisms which reside there. The entrapped material is digested and broken down into simple in- organic salts which are passed through the filter (Huisman, 1978).

There is strong evidence that up to 50% of bacteria in natural fresh water may be adsorbed onto the surface of suspended solids (Milne, Curran & Wilson, 1986). This material is trapped on the surface of the filter.

In conventional SSF it has been found that most of the reduction in indicator organisms occurs in the first 200mm of the filter (Williams, 1984). The reduction in organic matter through bio-chemical oxidation in the body of the filter further starves the bacteria which escape the "shmutzdecke" (Huisman, 1978).

Accounts of the bacteriological efficiency of SSF seem to vary in the literature. Huisman (1978) quotes reductions of

10^4 to 10^3 in total bacteria, and E-coli reductions of 10^3 to 10^2. Williams quotes the number of samples in which the E-coli exceeds the limit of nil/100ml as 50%, while Paramasivam and Sundaresan (1979) quote 89% of samples as being free of E-Coli. It is therefore considered necessary for SSF effluent to be chlorinated, but in situations where chlorination is unlikely to be sustainable, SSF remains the most suitable form of water treatment.

4.4 Design criteria

Figure 4.2 indicates the main features of a typical SSF. The plant is not fully described here but the main features are the inlet/outlet control, the filter surface (the "schmutzdecke"), the body of the filter and the underdrain collection system.

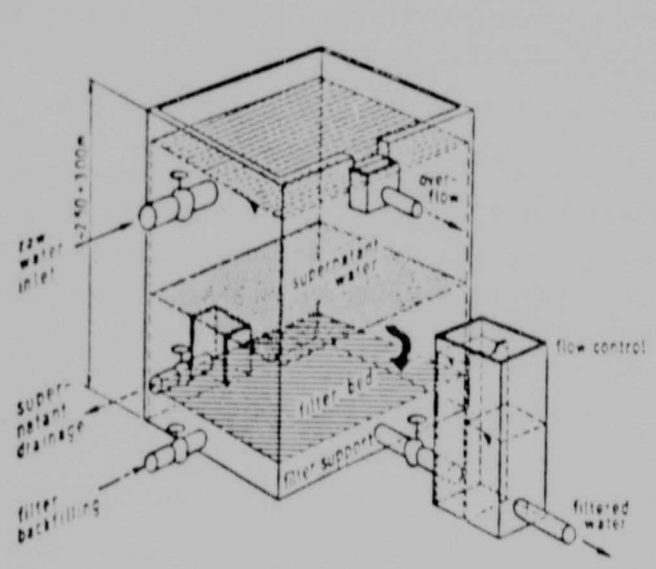


Fig. 4.2 Typical slow sand filter (Huisman,1978)

4.4.1 Flow rate

It has been found that the flow rate in the filter does not significantly affect the treated water quality (Huisman, 1978). In fact the quality has been seen to improve with a faster rate, but as indicated above the filter run will be shortened if the rate is increased. A standard which is often applied is a rate of 0.1 - 0.2m per hour. This may be increased to 0.3m at times of heavy demand or when alternate filter beds are out of commission for repairs or cleaning. The rate of filtration, together with the demand, will determine the filter area required. If the demand is D m^3/day and the filter rate is R m/h, then the filter area, A (m^2) is given by equation 4.4 :-

$$A = D/(24 \times R) \quad \ldots\ldots\ldots\ldots \quad (4.4)$$

Hence for a demand of 75m^3/day for a village of 1500 people, with a design rate of 0.15m/h, the area of the filter required will be 20.8m^2.

In many rural situations the SSF is only operated for some 8 to 10 hours a day because of the availability of staff. This means that the filter is run on a an intermittent basis which has been shown to produce an effluent of seriously reduced quality (Paramasivam & Sundaresan, 1979). To avoid this the depth of supernatant should be permitted to reduce under falling head conditions during the daily inoperative period, instead of closing down the filter altogether.

The simplest flow control mechanism is the constant flow, reducing rate method. The author has visited a rural slow sand filtration plant in Malawi where there

were no skilled operating staff. The flow control comprised simple instructions to an unskilled operator that the supernatant level in the filters must be maintained at a given level. When the flow level at a v-notch outflow weir drops below a certain point, the filter surface requires scraping.

4.4.2 Filter media

Fine uniform sands are the most suitable filter medium with an effective particle size (ES) of .2mm and a uniformity coefficient (UC) of 2. The more uniform the grain sizes, the greater the porosity of the filter bed. These characteristics are determined from a sieve analysis of the filter sand.

The effective size is defined as the sieve size (or particle diameter) through which 10% of the sample will pass (d_{10}). The uniformity coefficient is the ratio of the sieve size through which 60% of the sample will pass and effective size (d_{60}/d_{10}). See Fig 4.3

4.4.3 Shading

When filter supernatant is open to sunlight, the growth of algae will be stimulated. This may be expected to block the filter bed and reduce the length of filter runs but pilot plant research has not indicated this (Paramasivam, 1979). No indication was found of differences in effluent quality between shaded or open filters, but scraping of the surface of filters may be hindered by the presence of prolific algae growth.

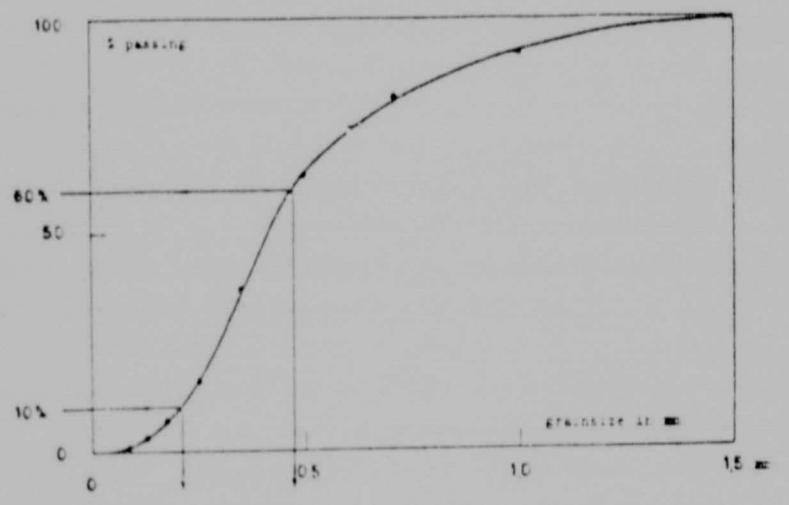


Fig. 4.3 Typical Filter sand Grading (Huisman, 1978)
ES : d_{10} = 0.2mm UC : d_{60}/d_{10} = 0.47/0.2 = 2.24

4.4.4 Operation and maintenance

One of the major causes of failure of SSF plants, however well designed, is inadequate training of operators and inadequate maintenance and supervision (Haijken & Turrell, 1978). Operators must be trained in more than just the minimum requirements for

operating the plant. They need to be provided with background information, giving them a basic understanding of the process. The caretaker must also be provided with the necessary tools, equipment and spares, and receive technical, financial and administrative support, both from the community and from the water supply agency (Kerkhoven, 1979).

4.4.5 Community participation

The success of a water supply and treatment project depends on the support of the community and is enhanced if the community ultimately owns and takes responsibility for running the system.

The establishment of a local organization, which has the support of the community, is essential to administer supply, collect revenues and pay the operator. This implies that the community must accept the supply, understand its advantages and be prepared to support the scheme in the long term.

The support of the community is generally stronger if they are involved from the beginning of the project, not only on a consultative basis, but as decision makers. If the project is clearly understood at each phase and if the community bears some of the cost, sustainability is enhanced. (Kerkhoven, 1979; Haijken & Turrell, 1978)

5. INTERMITTENT SLOW SAND FILTRATION

5.1 Introduction

The primary objective of the project was to find a method of treating water on a household basis in conditions where there are no other alternatives. The concept of batch loading, which is easily assimilated into the daily routine, was considered most likely to succeed but the literature indicated that intermittent loading of conventional SSF seriously affected the bacteriological efficiency of the process. A preliminary plant was designed with a 210 liter drum cut in half. The results from this plant were encouraging and justified further and more detailed study and testing. The plant was modified and the final design is shown in figure 5.1.

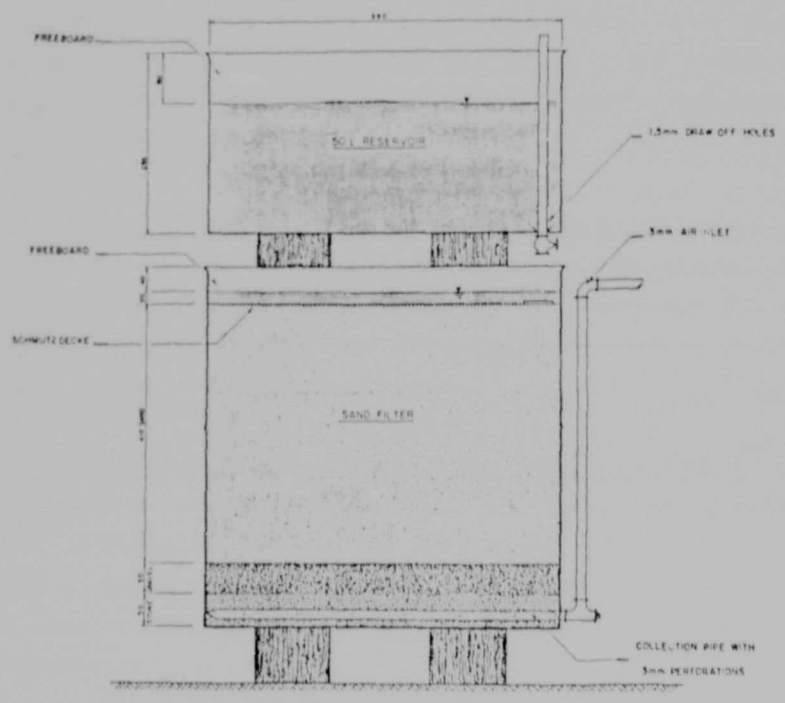


Fig. 5.1 Small scale domestic filter plant

5.2 Design criteria

The design criteria for the plant were the following :

- To provide drinking and cooking water for one family. Daily per capita drinking water demand is 2.3 litre (Alcock, 1986). The plant has a capacity of 50 l per day which, with an average family of 8 persons, provides 6.25 litre per capita per day.

- Simple operation. The plant must be capable of being operated by people with low literacy levels. It is people who have least resources who are most in need of this level of technology and if they are unable to operate the plant, the objectives of the project will not have been achieved. This is why a daily batch loading method for running the plant was chosen. A simple instruction to load the plant once a day, at the same time of day, using two 25 l plastic containers is likely to be sustainable.

- Minimal maintenance requirements. A plant which requires a lot of maintenance may fail either because the maintenance is not done, or because it is done incorrectly. Indicators of when maintenance is required should be simple and obvious.

- Constructed from locally available materials. This criterion takes into account not only the availability of materials, which is important if costs are to be kept to a minimum, but the need for the user to perceive the plant to be a familiar and understandable object.

- Minimum local skills required to construct. It is unlikely that any plant could be constructed with no skills at all. The need therefore is for a design that employs minimum skills and tools for construction. An individual or small concern could derive an income from constructing the plants on a scale appropriate to the local market.

- The plant must be acceptable to users. No matter how effective or well tested a design may be, if it is found to be unacceptable to the user the design is a failure. Reasons for unacceptability may range from the color, because it cuts across established practices and customs, to a desire by prospective owners for a new drum rather than a reconditioned, second-hand one. Discussions with prospective users must be held so that a full understanding of their needs and perspectives is obtained.

- The treated water must be acceptable to users. Water quality is subjectively assessed by most people, with such aspects as temperature, taste, smell and appearance being the main criteria. No matter how good the bacteriological quality of the water, if it is not acceptable to the user the design will fail.

- The bacteriological quality must be substantially improved without the use of chemicals. This is the main objective of the project. The single biggest health hazard in rural areas is water related disease and it was with a view to reducing this risk that the plant was conceived. Chemical disinfection of water is not a sustainable solution because of the expense and lack of availability of chemicals. The plant must therefore reduce bacteria without using chemicals.

- The cost must be as low as possible. The people for whom the plant is designed are among the poorest in community. It is essential therefore that the costs be kept as low as possible. The largest single component cost is the drum. Users have expressed a preference for new drums rather than reconditioned ones. This increases costs by about 50%.

5.3 Design and construction

The design of the plant is simple in appearance but each aspect has been carefully considered. Changes should not be made to the design unless they have been equally carefully considered.

5.3.1 The drum

The primary component of the design is the 210 l galvanized iron drum. The drum must be complete with a sealed lid with the standard large and 19mm bungs. The ideal is to use a new drum but a second-hand, reconditioned drum may be used depending on the original contents. A second-hand drum which has held any toxic chemical must not be used for obvious reasons as water from the filter will be directly consumed. In all instances the drum must be thoroughly cleaned and rinsed.

5.3.2 Cutting and preparation of the drum

A 210 l drum is 851mm deep and 560mm in diameter with ring moldings round the circumference at 1/3 positions. Each 1/3 section has a depth of 285mm. 50 litres occupies 203mm depth in the drum. Therefore if the drum is cut at the top 1/3 and this is inverted to form a

reservoir, there will be a freeboard in the reservoir of 82mm. The remaining 2/3 has a depth of 570mm. If the filter medium has a porosity of 40%, a filter depth of 507.5mm is required to contain a nominal 50 l within the filter. If this is rounded to 510mm with a minimum of 20mm of standing water at the filter surface, the freeboard in the filter section is 40 mm.

To construct the filter, the drum is cut at the top 1/3 ring and the top is inverted to form the reservoir with the bottom 2/3 being the filter section. The drum is best cut with an angle grinder but a hack saw could be used. The newly cut lip is then filed smooth and all sharp snags are removed. A hole is made in the side of the filter section near the bottom of the tank, through which the collection pipe passes. A 4mm drill bit is used for this purpose and a number of holes are drilled in a circle to create one hole large enough for the collection pipe to be passed through. The hole is then filed clean. It should be just large enough to accept the pipe, because If it is too large leaks may occur.

5.3.3 Fittings

The fittings required for each filter are as follows:- (All pipes and fittings are 12mm galvanized iron unless otherwise indicated.)

1 x 330mm reservoir inlet pipe with 50mm of thread at one end and the other end blank.
1 x 12 - 19mm adapter with blank end sawn off.
1 x valve.
1 x 580mm collection pipe with one end blank and the other with 40mm length of thread.
2 x nuts
2 x washers
1 x T piece
1 x stopper
1 x 470mm delivery pipe threaded both ends.

1 x elbow
1 x threaded hose connection.
2 x 500mm long 75x50mm timber supports.

5.3.4 The reservoir

The reservoir is designed both as a storage facility and as a sedimentation basin. Raw water is poured into the reservoir and flows through four 2mm holes drilled in the bottom of the inlet pipe and hence into the filter section below. The inlet pipe is designed so that the top protrudes above the top of the reservoir. When the 2mm inlet holes get blocked they can be easily cleared by blowing down the inlet pipe. The inlet pipe is passed, via a 19 - 12mm adapter, through the bottom of the reservoir. On to the protruding end of the pipe is threaded a tap which regulates the flow from the reservoir to the filter. The reservoir is supported on the filter section in such a way as to ensure that the tap is freely accessible and that it does not touch the water surface in the filter during operation.

5.3.5 The filter section

The first step : The collection pipe.
The unthreaded end of the pipe is closed by flattening it with a heavy hammer. 2mm holes are then drilled on both sides of the pipe at 100mm spacing. A nut is threaded onto the pipe, together with a washer, and the threaded end is pushed through the already prepared hole in the filter wall from the inside. The pipe is secured with a second washer and nut in such a way as to ensure that the holes on both sides of the pipe are on the horizontal plane.

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