Performance of cotton mat as pre-filtration unit for groundwater recharging

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Recharging groundwater through rooftop-harvested rainwater has immense potential. In order to manage the instant increase in storm run-off generated from high-intensity rainfall events, a filtration system with high-flow rate is required. Filtration through sand beds is a technique accepted world-wide, but its filtration rate reduces drastically with increase in inflow sediment load. For maintaining the pace in filtration rate through sand bed, a highly efficient, low-cost pre-filtration unit fabricated using cotton mat is recommended. The performances of three- and four-layer cotton mat filters have been evaluated using inflow sediment concentration of 50 and 100 mg/l. Results show that the four-layer cotton mat filter starts delivering sediment-free water much earlier than the three-layer filter, especially at the lower inflow sediment concentration. Moreover, the sediment trapping pattern is influenced by inflow sediment load and the first layer of the cotton mat. Experimental results show that the performance of the cotton mat filter is excellent and can be used as a cost-effective and reliable pre-filtration unit for handling the instant increase in storm run-off during groundwater recharging.

Groundwater has the remarkable distinction of being a highly dependable and safe source of water supply[1]. The introduction of diesel engine and electric motor operated pumps in the 20th century made it convenient to tap groundwater from deeper aquifers[2]. Ever increasing demand from agricultural, domestic and industrial sectors has led to the overexploitation of fresh groundwater beyond sustainability limits. This has resulted in the widespread and progressive depletion of water level all over the world. Zektser and Lorne[3] have assessed that groundwater withdrawal (globally) ranges between 600 and 700 km^3/year. Groundwater table in many Indian states is also falling rapidly[4]. The country is experiencing water stress and it is high time to shift the thrust of the policies from 'water development' to 'sustainable water development'. Groundwater is replenished through rainfall and rivers/streams to the extent of about 50 and 35 million hectare metres (M ha m) respectively[5]. The total annual rainfall of the country is 400 M ha m, whose distribution is erratic in space and time. The climatic variability has drastically changed the rainfall pattern, which has further widened the variation in water availability spatially and temporally. The longer duration low-intensity rainfall events have now been replaced with smaller duration high-intensity rainfall showers. This changed pattern of rainfall is further responsible for reduced recharging of the aquifers. As the climatic extremes such as droughts and floods are further increasing the stress on existing groundwater resources[6], there is a need to focus on the groundwater management issue[7]. To sustain groundwater reservoirs, artificial recharging of aquifers using harvested rainwater has been recognized as one of the important strategies for groundwater management. Few other benefits of rainwater harvesting (RWH) are that it reduces the stress on the demand for potable water, controls storm water run-off[8,9], and effectively reduces the urban waterlogging problem[10]. RWH is a centuries' old practice and is adapted all over the world through various location-specific techniques. Broadly, the catchment for RWH can be classified into ground surface and rooftop. Other than storing the harvested rainwater in lined tanks (directly or after filtration), it is usually guided to recharge groundwater in assistance with the artificial techniques which include small check dams (earthen or masonry), dug-out ponds, subsurface tanks, infiltration pits or half-moon terraces, etc. The basic purpose of such techniques is to increase the residence time of water on the surface which eventually enhances the groundwater recharge. However, these techniques require considerable land area and may not be feasible within municipality boundaries of urban areas. Under this situation, storing harvested rainwater in optimum-sized cisterns or lined tanks for household activities[11], and/or recharging of aquifers through pits or recharge shafts are the suitable options. An efficient filtration unit is an integral component of an artificial recharging system. Most commonly, sand-bed filters are used for sediment-free water while recharging through shafts or wells in large fields. The excess sediment load in the storm run-off drastically reduces the filtration process through sand beds. Typically, the sand-bed filters are suitable under regulated inflow conditions. It is already mentioned that rainfall showers are more intense now; therefore, the major challenge is to efficiently manage the instantly generated storm run-off to avoid its wastage. For this purpose, a sand bed with huge filtration surface is required, which may not be a suitable option in urban conditions. Moreover, frequent washing of the sand-bed filter to revive its storm water-handling capacity is a tiresome and time-consuming task. Nonetheless, the problem of slow filtration rate and short service life of the sand bed can be solved by pre-filtering the storm run-off. The principle processes by which sediments are brought into contact with the sand grains (either sand bed or aquifer) include: (i) screening, (ii) sedimentation, (iii) inertial and centrifugal forces, (iv) diffusion, (v) mass attraction, and (vi) electrostatic and electro-kinetic attraction. By the use of pre-filters, the first two processes (i.e. screening and sedimentation) can be efficiently completed before diverting the outflow to the sand bed. Practically, these are the two major processes which are responsible for early clogging of the sand bed depending on the sediment load in the inflow. It indicates that the introduction of pre-filtration device can delay the clogging of the sand bed to considerable extent. The use of pre-filters before sand filtration is an accepted technique, but their use is limited to screening large-sized particles and other organic content in the water[12] and usually beds containing pebbles, gravels or other coarse-sized materials are preferred for the purpose. However, its inability to trap even coarse sand of size 0.5 mm along with the heavy infrastructure discourages urban users to make it an essential component of the filtration system. Hence, the aim of the present study is to design a pre-filtration unit that can trap sediments other than colloidal particles, can handle the instant increase in inflow rate, have light infrastructure; can be maintained easily and cost-effective.

The various natural fibrous materials like coir, jute, cotton, bamboo, cereal straws, etc. and other products derived from these natural fibres are regularly used in civil constructions, filtration, biological denitrification and screening processes[13–16]. For water treatment, fibrous adsorbents have an advantage of fast adsorption rate and ease of handling when compared with granular adsorbents and powdered adsorbents[17]. Since the fibrous materials are light in weight and flexible, the desired shape and filtration surface area can be achieved conveniently according to the available area and geometry of the space. However, for making pre-filters very fine fibre is required and the processing cost for achieving this fineness for jute and coir may be quite high. On the other hand, raw cotton fibre without any processing can be used to fabricate the filter. Therefore, for the present study, cotton fibre-based mat has been selected with the aim to test its efficiency in filtering the sediment-laden storm run-off.

Experimental set-up

The cotton mat (5 cm wide and 0.26 cm thick) was procured from the market for developing the filtration unit. A PVC (polyvinyl chloride) pipe of 110 mm diameter and 3.5 m length was plugged at the bottom with a cap. Since the drilling of holes beyond 16–18% of the pipe surface area severely affects its structural strength, it was decided not to exceed the limit by 18%. Holes were drilled at the bottom 15 cm length of the pipe.

$$\text{Total surface area of the 15 cm long PVC pipe} = 518.36 \text{ cm}^2. \quad (1)$$

$$\text{Surface area drilled} = 0.18 \times 518.36 = 93.305 \text{ cm}^2. \quad (2)$$

Holes with diameter 16 mm each were drilled on the PVC pipe in a zigzag pattern and their number calculated as follows:

$$\text{No. of holes} = 93.305/\text{area of one-hole} = 46. \quad (3)$$

Cotton mat in three layers was wrapped over the portion of the pipe with holes. Two units with the mentioned specifications were fabricated. Similarly, two more units were fabricated with the same materials and specifications, except with a modification that instead of three, four cotton mat layers were wrapped over the pipe. Performance of each filter was tested with turbid water of sediment concentrations, viz. 50 and 100 mg/l. The two sediment concentrations were prepared by mixing kaolinite clay in tap water and stored in an overhead tank of 500 litre capacity. The turbid water was allowed to pass through the filter at constant head of 3.2 m, which was chosen keeping in mind the general height of a single-storey building (Figure 1).

Results and discussion

Temporal variation in outflow rate was monitored during experiments on two sets of filters with two sediment concentrations. Filtrate samples for monitoring outflow sediment concentration were also procured at different time intervals. The experimental results were analysed for calculating the flow rate (FR), cumulative flow (CF), outflow sediment concentration (OSC) and trapped sediment load (TSL). Figure 2 shows the variations in cumulative flow with time for all the four filters. The figure also shows the change in OSC in the filtrate with time. General trend for all the four filters shows that CF increases with a deceasing margin. There is a remarkable difference between CF through the filters (whether three- or four-layer) with different inflow sediment concentrations (ISCs), viz. 50 and 100 mg/l. Moreover, with time this difference in CF further increases. However, the difference between CF through the three-layer cotton mat (3 LCM) filter (i.e. curve 2) and the four-layer cotton mat (4 LCM) filter (i.e. curve 1) after 400 min is not significant at a higher ISC of 100 mg/l (Figure 2). It is a well-known fact that sediment load will be trapped to a maximum extent by the first layer of the mat, which decreases subsequently for the successive mat layers. Therefore, the first layer becomes responsible for guiding the outflow rate through the filter. Moreover, at lower ISC of 50 mg/l, CF through the 3 LCM filter (i.e. curve 4) remains remarkably higher than the 4 LCM filter (i.e. curve 3). The analyses indicate that the influence of the number of cotton mat layers on FR becomes ineffective as ISC increases excessively. The results also show that FR through the 3 LCM filter is higher than the 4 LCM filter at lower ISCs.

All the filter materials have their own limits in trapping the sediments from the inflow, which depend on the porosity and structural arrangement of the filter material. From the experimental results, it is found that the extreme limit of cotton mat filter for sediment trapping does not fall below 8 mg/l, irrespective of the number of mat layers. For example, the 4 LCM filter started delivering OSC of 8 mg/l only after 106 min (see solid marker '♦' in Figure 2) for ISC of 50 mg/l, whereas this time value increased to 243 min (see solid marker '•' in Figure 2) for ISC of 100 mg/l. On the other hand, the 3 LCM filter took 406 min (see solid marker '▲' in Figure 2) for delivering the desired OSC for ISC of 50 mg/l, which further increased to 459 min (see solid marker '■' in Figure 2) for ISC of 100 mg/l. Results show that at higher ISC, FR through the 4 LCM filter is not significantly different from that of the 3 LCM filter, but the sediment trapping capacity of the former is substantially higher than the latter. Moreover, the 4 LCM filter starts delivering the desired quality of water much earlier than the 3 LCM filter, especially at low ISC. When one is not sure about the extent of inflow sediment load in storm run-off, 4 LCM filter should be preferred for attaining the full performance. The 3 LCM filter may be used for higher outflow rate, once we are sure that the sediment load in the inflow will not be high.

In Figure 3, sediment trapping patterns with time and flow rate are graphically

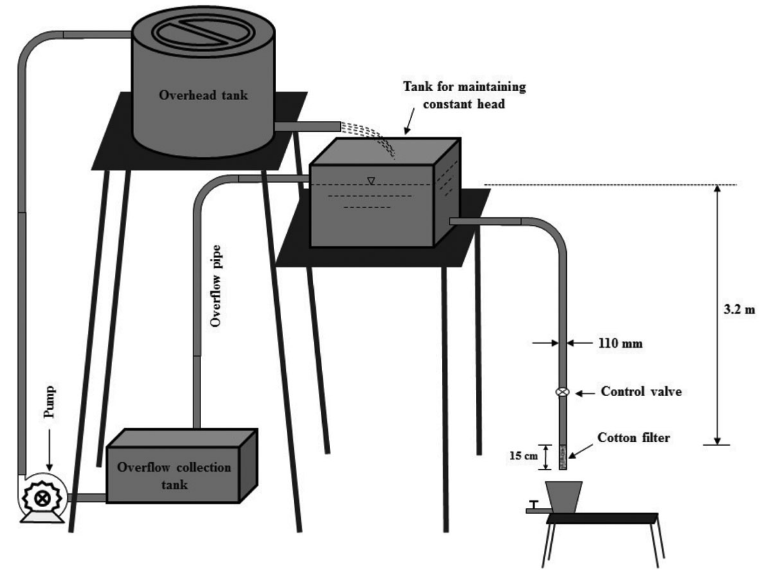

Figure 1. Schematic sketch showing the experimental set-up.

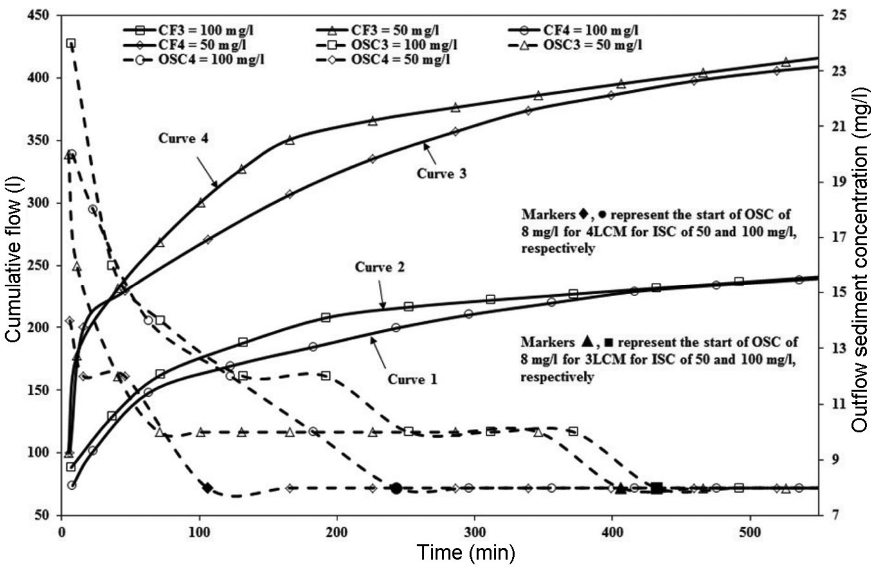

Figure 2. Graph showing variation in cumulative flow and outflow sediment concentration with respect to time.

presented for all the four filters. During early times, trapping of the sediments is very high which is reflected by a sharp decline in the outflow rate through the filters. With increase in time, TSL curves with 100 mg/l ISC (i.e. curves 3 and 4) follow a much differentiated path from the curves with ISC of 50 mg/l (i.e. curves 1 and 2). However, an interesting fact is that the TSL pattern is not much affected by the number of cotton mat layers. This is because most of the sediment load is trapped by the first layer of the cotton mat. The above discussion has shown that the sediment trapping pattern is influenced by ISC and the first layer of the cotton mat. However, delivering the water with minimum possible sediment concentration is beyond the limit of a single-layer cotton mat. Hence delivering time to the minimum possible sediment concentration of water (i.e. 8 mg/l) decreases with an increase in cotton mat layers from 3 to 4 (compare the time difference between solid markers '▲' and '♦' for 50 mg/l ISC and between '■' and '●' for 100 mg/l in Figure 3). The analyses show that with increase in the number of cotton mat layers and decrease in sediment load in inflow, the desired quality of water is attained earlier. It is also evident that the 4 LCM filter along with the sand-bed filter may be preferred as a reliable filtration unit for groundwater recharging in the low-rainfall or drier regions. On the other hand, if it is planned to store the harvested rainwater in cisterns and surface storage tanks for non-domestic uses without passing the water through sand-bed filter, the 3 LCM filter may be preferred as its filtration rate is comparatively higher than the 4 LCM filter. Major benefit of passing the storm run-off through cotton mat filters is that this operation drastically reduces frequent cleaning of sediments collected in the storage structures.

Recommended filter

Before recommending the final design criteria of the filter, it is required to evaluate the service life of the cotton mat. For this, there is a need to evaluate its choking limit. The experimental results have shown that the maximum value of TSL on the choking of filters among all the four experiments is 21.11 g. Therefore, the choking limit of the cotton mat is calculated using eq. (2) as

$$\text{Choking limit of cotton mat} = 21.11/93.305 = 0.226\ \text{g/cm}^2. \tag{4}$$

Practically, one does not have to wait for the complete cessation of flow. Considering the 50% lesser choking limit (for the design purpose), the service limit for the filter is

$$\text{Service limit for the filter} = 0.226 \times 0.50 = 0.113\ \text{g/cm}^2. \tag{5}$$

To fabricate a filter, a skeleton was required which can provide maximum possible open surface area along with the strength. A 3 mm diameter steel wire net with mesh size $2.54 \times 2.54\ \text{cm}^2$ is an appropriate choice (Figure 4 *a*). The aim is to fabricate the skeleton in cylindrical shape from the steel wire net of approximate diameter 11 cm. Therefore, the number of complete squares that will be covered in the circumference is 14. With 14 squares, the actual circumference of the cylindrical skeleton is

$$\text{Actual circumference} = 14 \times 2.54 = 35.56\ \text{cm}. \tag{6}$$

Further, it is proposed to fabricate a ~ 100 cm long filter. Hence the number of complete squares that will be covered along the length is 40. Therefore, the actual length of the cylindrical skeleton will be

$$\text{Actual length} = 40 \times 2.54 = 101.60 \text{ cm}. \quad (7)$$

The total surface area of the cotton mat will be equal to the total cylindrical surface of the skeleton and can be calculated by multiplying eqs (6) and (7)

Total surface area of mat

$$= 101.60 \times 35.56 = 3612.896 \text{ cm}^2. \quad (8)$$

Here it is worth mentioning that while fabricating the cylindrical shape from the steel wire net, steel wires running along the length are kept outside (Figure 4 *a*) to avoid contact between the cotton mat and circumferential wires. We need to wrap the cotton mat along the circumference of the cylinder and because of this the accumulated length of the wires in the skeleton that is in touch with cotton mat can be calculated using eqs (6) and (7) as

Accumulated length

$$= (14 + 1) \times 101.60 = 1524.00 \text{ cm}. \quad (9)$$

Since the cotton mat is wrapped on the skeleton with appropriate stiffness and due to its inherent cushioning nature, it gets pressed along the steel wire and considerable surface of the mat becomes unavailable for filtration. Figure 4 *b* shows a schematic sketch which clearly depicts the surface area of the cotton mat which will not be available for the filtering of sediment-loaded water. This width has been found equal to ~2 mm. Thus, the total surface area of cotton mat in touch with the skeleton is

Total surface area

$$= 1524.00 \times 0.20 = 304.80 \text{ cm}^2. \quad (10)$$

The effective surface area of cotton mat available for filtration process can be calculated using eqs (8) and (10) as:

Effective surface area

$$= 3612.896 - 304.80 = 3308.096 \text{ cm}^2. \quad (11)$$

The effective surface area (eq. (11)) is 91.56% of the total surface area of the cotton mat wrapped on the steel wire net cylindrical skeleton which is remarkably higher than the PVC pipe in which case we cannot exceed the 18% limit. The service limit of the fabricated filter is evaluated from eqs (5) and (11) as:

Service limit

$$= 3308.096 \times 0.113 = 373.81 \text{ g}. \quad (12)$$

It indicates that when TSL becomes equal to 373.81 g, cleaning of the filter is required. It is worth mentioning here that after excluding the first storm run-off of the season, the average sediment concentration in run-off generated on the cemented roof generally did not cross the limit of 6 mg/l. This limit may increase with the presence of soil-laden pots on the roof. In that case, the service life of the filter will decrease, which can be compensated either by increasing the number of filtration units or by increasing its dimensions. Considering the average sediment concentration in the run-off generated on the cemented roof equal to 10 mg/l, the capacity of the filter for single-service life can be evaluated from eq. (12) as

Capacity of the filter

$$= 373.81/0.010 = 37{,}381 \text{ litre}. \quad (13)$$

This capacity of the filter can easily handle the run-off from 100 m^2 roof area for 18 storms of intensity 2 cm/h. From the roof area and filtering capacity of the cotton mat filter, the required number of

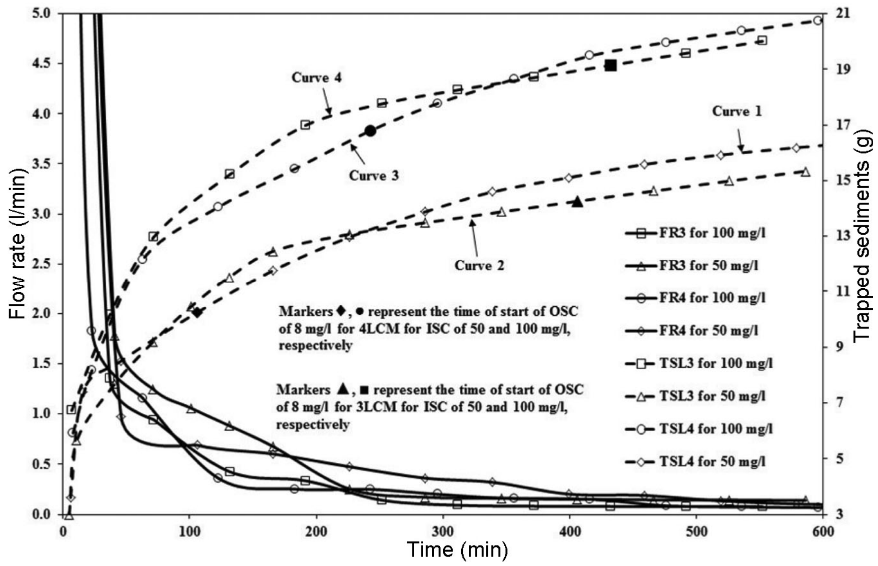

Figure 3. Graph showing variation in flow rate and trapped sediment load with respect to time.

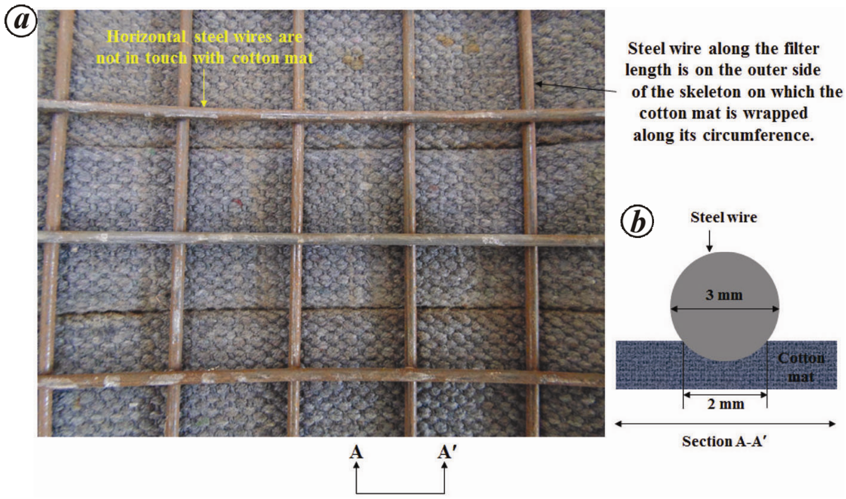

Figure 4. ***a***, Inside view of a cotton mat filter. ***b***, Schematic sketch showing the loss of surface area due to contact of steel wire with cotton mat.

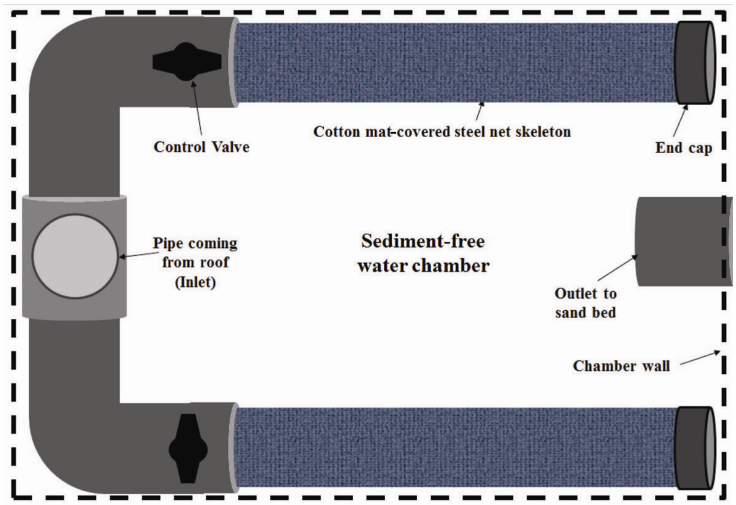

Figure 5. Schematic sketch showing the cotton mat filter in the chamber. Two control valve-operated units are shown.

filtration units can be calculated easily. Moreover, it is always advisable to prepare or install one or more extra unit(s) from the evaluated quantity (as shown in Figure 5). All the units should be provided with control valve for regulating the inflow. When any one unit is detached for cleaning, the others will remain in service. Most importantly, the cost of one unit of the 4 LCM filter (including material and fabrication) is only INR 350. Thus, such a highly cost-effective and efficient pre-filtration unit should be an integral component of the RWH system in residential, commercial, industrial, educational and religious buildings. Certainly, the query regarding the durability of the cotton mat may come to one's mind. Generally, in drier regions the pattern of rainfall showers is intermittent in nature. Except few showers which may occur continuously during monsoon season, generally enough time between two showers is available for the mat to dry. According to the authors' experience, the service life of the mat is not less than 3–4 years even under such alternate wetting and thawing conditions. Nonetheless, the mat is cheap enough that one can change it even after one season.

Conclusion

Groundwater recharging using the rooftop-harvested rainwater through recharge shafts has immense potential and is a suitable option in city conditions where availability of appropriate space is a major constraint. To avoid clogging of the aquifers, a highly efficient filtration system that can handle the instant increase in storm run-off is required. For maintaining the filtration rate through sand bed, a highly efficient, low-cost pre-filtration unit fabricated using cotton mat is recommended. The performances of the three- and four-layer cotton mat filters have been evaluated under constant head of 3.2 m using ISC of 50 and 100 mg/l. It is concluded that the 4 LCM filter starts delivering the sediment-free water much earlier than the 3 LCM filter, especially at lower ISC. The results show that the sediment trapping pattern is influenced by ISC and the first layer of the cotton mat. It can also be concluded that the 4 LCM filter can be opted as a cost-effective and reliable pre-filtration unit for groundwater recharging in low-rainfall areas. For storing the harvested rainwater in tanks for non-domestic uses without passing through the sand-bed filters, the 3 LCM filter may be a good option.

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