# Performance of Dual Flow Grass Filters Integrated with Groundwater Recharge System for Stormwater Treatment – A Laboratory and Field Study

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## ABSTRACT

*A dual flow multimedia stormwater filter integrated with a groundwater recharge system was developed and tested for hydraulic efficiency and pollutant removal efficiency. The influent stormwater first flows horizontally through the circular layers of planted grass and bio-fibres. Subsequently the flow direction changes into vertical direction so that water moves through layers of pebbles and sand and finally it gets recharged to the deep aquifers. The media in the sequence of Vegetative medium: Bio-fibre- Pebble: Sand were filled in 9 proportions and tested for the best performing combination. Three grass species, viz., Typha (*Typha angustifolia*), Vetiver (*Chrysopogon zizanioides*) and St. Augustine grass (*Stenotaphrum secundatum*) were tested as the best performing vegetative medium. The adsorption behaviour of Coconut (*Cocos nucifera*) fibre, which was filled in the middle layer, was found out by a series of column and batch studies. The dual flow filter showed an increasing trend in hydraulic efficiency with increase in flow rate. The chemical removal efficiency of recharge dual flow filter was found very high in case of K+ (81.6 %) and Na (77.55%). The pH normalizing efficiency and EC reduction efficiency were also recorded high. The average removal percentage of Ca2+ was moderate, while that of Mg2+ was very low. The filter proportions 1:1-1:2 (plant: fibre- pebble: sand) showed much superior performance compared to all other proportions. Based on the estimated annual costs and returns, all the financial viability criteria (IRR, NPV and BCR) were found favourable and affordable to farmers for investment on developed filtration system.*

**Keywords:** *Recharge filter, vegetative media, bio-fibre, pollutant removal efficiency, hydraulic efficiency,*

One of the major rainwater management strategy is subterranean rainwater harvesting which throws light on the ways and means for augmenting the groundwater aquifer storage and supplies. The surface runoff produced from intermittent storms is generally recharged into deep aquifers by means of recharge wells, shafts or simple catch pits.The major contaminants of storm runoff are mainly silt load, residues of pesticides/ weedicides or fertilizers, organic pollutants-both human and plant origin, heavy metals and other chemical load from industries. As Lee et al. (1999) and Taylor & Lee (1998) discussed, it is important to be certain that the infiltration system does not lead to pollution of groundwaters that would be a threat to their use for domestic and other purposes. Moreover, in case of shallow groundwater systems, there is a potential for pollution of surface waters through stormwater infiltration. The degree of contamination is very much felt in areas of well irrigation, where the associate problems like salinity, alkalinity and hard water make the groundwater usage restrictable unless otherwise efficient surface and subsurface filtration mechanisms could eventually help recharge the groundwater with relatively pure rainwater percolations. The recovery of relatively good groundwater for storage and use warrants the usage of a variety of filtering mechanisms as to the need. The design and evaluation of appropriate location specific, bio-degradable and cost-effective filter media are thus a highly vital issue.

*Kamra et al. (2004)* investigated the usefulness of a small recharge shaft with filtration bed constructed in a farmer's field at a village in North India. Kambale et al. (2009) in their study, evaluated the effect of variable thickness of coarse sand (CS), gravel (G) and pebble (P) layers of the filtration unit of a recharge shaft on the recharge rate and the sediment concentration of effluent water. It was observed that higher thickness of CS resulted in reduction of the recharge rate, but improved the filtration of the effluent. Overall, considering both the recharge rate and sediment concentration of the effluent, they suggested that the filtration layer thickness ratio of 1.5 : 1 : 3 (CS : G : P) would be the optimal design of the filtration unit to facilitate higher recharge and perform better filtration of the turbid water. Another study on sinkhole filter found that it as an effective management tool in order to reduce inputs of pathogens to groundwater aquifers. But it had no filtering effect on solutes like nitrate (Boyer, 2008).

Grass swales and filter strips are among the simplest and most cost-effective form of stormwater control measures. Swales are open vegetated (generally grass) drains, which provide stormwater filtration prior to discharge to downstream drainage systems or receiving waters. Buffers or filter strips are grassed surfaces aligned perpendicular to the direction of flow, which are used to filter particulate matter and associated pollutants from stormwater prior to its entry into the adjacent receiving water. Whilst traditional features in rural environments, these grass filters are increasingly being used in urban areas for control of polluted urban stormwater runoffs (Deletic & Fletcher, 2006; Duchemin & Hogue, 2009). Calheiros et al. (2009) experimented on two-stage series of horizontal subsurface flow constructed wetlands with *Phragmites australis* and *Typha latifolia* and observed high removal efficiencies of organics from tannery waste water. The results of studies on performance evaluation of a hybrid filter consisting of grass filter strips and other filter media such as gravel, sand and fibres are reported in this paper.

## METHODOLOGY

A dual flow filtration mechanism was designed, developed and evaluated for groundwater recharge of surface runoff. The real time recharge filter was a combination of bio-filter and media filter. The water flows first longitudinally through the outer bio-filter ring planted with vegetation and then through fibre filled middle ring. Afterwards it flows transversely through vertical layers of pebbles and sand and finally towards the groundwater through the perforated tubes in the recharge well (Fig. 1). The filter was designed with such an objective that the drinking water standards have to be met as the water is directly getting added to the groundwater reserve. A model of the dual filter device was fabricated and used for laboratory studies on hydraulic efficiency and quality improving efficiencies.

The dual flow recharge filter was also designed by using the first order kinetic (k - C*) model (Wong et al. 2006). A laboratory model of the dual flow filter, which has dimensional homogeneity to the designed real world filter system, was fabricated. The dimensions of the designed filter device and the model were of the ratio 3:2. The model consisted of three concentric rings of diameter 1.4 m, 1.1 m and 0.8 m respectively, where the depths of the first two rings were 0.4 m, while that of the inner one was 1.3 m. The inner ring served as vertical filter, while the outer two rings functioned as horizontal filters. The filter was made up of GI sheets and the walls of the inner and middle rings were perforated by holes of size 2 mm. A 3.61 m long LLDPE pipe of diameter 16 mm having holes at 10 cm interval was fixed along the circumference of the outer ring for supplying inlet water, while a 32 mm diameter PVC pipe regulated by a gate valve was attached to the bottom of the inner vertical filter for collecting filtered water samples.

Sand (mean particle size of 0.7 and uniformity coefficient 1.46) and river pebbles (mean particle size is 40 mm) were selected as fixed media for the inner ring and coir fibre was chossen as the filter media for the middle ring. Coir a natural vegetable hard fibre extracted from the exocarp of the fruit of coconut palm *Cocos nucifera*, which a 100 per cent organic biodegradable lignocellulosic fibre. The outer ring was filled with sandy loam soil (hydraulic conductivity 1.6 x10-4 m s-1) up to a depth of 30 cm, and planted with vegetation viz., Typha (*Typha angustifolia)*, Vetiver (C*hrysopogon zizanioides*) and St. Augustine grass (*Stenotaphrum secundatum*). The comparative efficiencies of these three bio-filter vegetative media in various proportions were tested. The adsorption behaviour of coir fibre, which was filled in the middle layer, was found out by a series of column and batch studies.

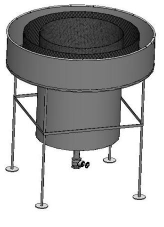

Fig.1. Dual flow recharge filter

The vegetative filter media were planted in the outer ring. Coir fibres were packed in the middle ring up to a height of 0.35 m with a packing density of 11.2 kg m-3. The inner ring of depth 1.3 m was essentially a vertical filter with two layers of filter media, viz., gravel (pebbles) and sand, as explained above. The former was filled as the upper layer, while the latter as the bottom one. The media in the sequence of *Vegetative media: Bio-fibre- Pebble: Sand* were filled in 9 proportions such as 1 : 1 – 1 : 1, 1 : 1 – 2 : 1, 1 : 1 – 1 : 2, 1 : 2 – 1 : 2, 1 : 2 - 2 : 1, 1 : 2 – 1 : 1, 2 : 1 – 2 : 1, 2 : 1 – 1 : 2 and 2 : 1 - 1 : 1.

A flow control valve was fixed in the inlet LLDPE pipe to measure and regulate the inflow. The inlet pipe was connected to a pump (0.125 HP self-priming centrifugal pump) and the water sump (500 L capacity plastic tank (Sintex). The filtered water was collected by means of a valve at the bottom of the inner ring.

The experiment was designed in Factorial CRD method and each experiment was replicated three times. The statistical analysis of variance was conducted and the difference between treatments means were tested for significance using standard ANOVA analysis. Ranking of major effects and their interactions were carried out using Duncan's new multiple range test.

The experiments were first conducted with well water and subsequently with semi-synthetic water dosed to the level of stromwater. The rate of inflow and outflow were measured by using a measuring cylinder and a stop watch. The inlet and outlet pressure heads was noted using precision pressure gauges fixed both in inlet and outlet pipes. The filtered water samples were collected as per standard methods in plastic containers and subjected to detailed water quality analysis for various chemical parameters using standard methods. The hydraulic efficiency, water quality improving efficiency and universal performance index (UPI) of various types of filter combinations were also computed.

*Hydraulic Efficiency:* Hydraulic efficiency (HE) is the measure of the fraction of the incoming stream that penetrates through the filter (Martinson and Thomas, 2003). The rate of inflow and outflow were measured in three replications and subsequently the amounts of water penetrated through and spilled over the filter were calculated.

HE = rate of outflow*100/rate of inflow = (Qin/Qout)*100
= (rate of inflow - rate of spilled over water)
*100 /rate of inflow …(1)

*Filter effectiveness :* The filter effectiveness can be expressed as the fraction of total particulates removed by the filter. For a certain chemical parameter, the average percent removal was calculated as follows (Hamoda et al., 2004):

% Ra = [(Ci-Co)/Ci]100 …(2)

Where, Ra = average percent removal of certain chemical parameter

C = concentration of a certain chemical parameter, subscripts 'i' and "o" refer to the inlet and outlet water of the filter device, respectively (mg L-1).

The same types of formulae were used for finding out the EC reducing efficiency and sediment removal efficiency. However since the pH has to be brought to the neutral value 7 by the filtration process, another equation is formulated to find out the pH normalizing efficiency, as given below:

$$\text{pH normalizing efficiency} = \left[\frac{pHi - |7 - \mathrm{pHo}|}{pHi}\right]100 \quad \ldots(3)$$

where,

pHi = initial pH of water before filtration

pHo = pH of water after filtration

The term filter effectiveness is the mean of the Ra values with respect to all analyzed physico-chemical parameters and the pH normalizing efficiency and it is identical to the overall quality improving efficiency (QIE), which is referred in the following text.

*Universal Performance Index*: The UPI (Universal Performance Index) is new terminology introduced and it is the weighted average of the hydraulic efficiency and quality improving efficiencies, giving extra weightage to the latter. The UPI can be calculated as follows:

$$\text{UPI} = \frac{1}{2(n+1)}\left[\text{HE} + 2*\sum_{i=1}^{i=n} QIEi\right] \quad \ldots(4)$$

where,

HE = hydraulic efficiency

QIEi = quality improvement efficiency with respect to ith parameter

n = total no of chemical parameters tested

Field evaluation of the best recharge filter combination, selected by laboratory experiments, was conducted at the PFDC farm of Department of Soil and Water Conservation, Tamil Nadu Agricultural University, Coimbatore (India). Apart from these, cost-benefit analyses were carried out for different types of filtration mechanisms. Along with the B-C ratio, net present value (NPV) and internal rate of return (IRR) were also computed using standard methods.

## RESULTS AND DISCUSSION

Hydraulic efficiency of the filter with various proportions and media was examined (Fig. 2). Media proportion 2:1-2:1 (plant: fibre- pebble: sand) performed best followed by the proportion 1:1-2:1. Since all the media performed almost on par, there was no significant difference among their hydraulic efficiency values. The higher hydraulic efficiency of proportion 2:1-2:1 could be due to comparatively high volume of pebbles, which is having very high hydraulic conductivity. On an average 52 % (range 39-61 %) of water was retained by the recharge filter. This result is in good accordance with 33 % (range: 15-83 %) retention of inflow water by a biofilter as reported by Hatt *et al*. (2009).

Hydraulic efficiency of the best filter combination was plotted against the flow rate as shown in Fig. 3. The hydraulic efficiency showed an increasing trend with increase in flow rate when the flow rate was < 0.08 L s-1. However, at higher flow rates (> 0.08 L s-1), the permeability of the filter showed decreasing trend with increase in flow rate. The rising limp of the graph resembles same phenomenon reported by Molini *et al*. (2007) based on hydraulic studies of a stormwater treatment device.

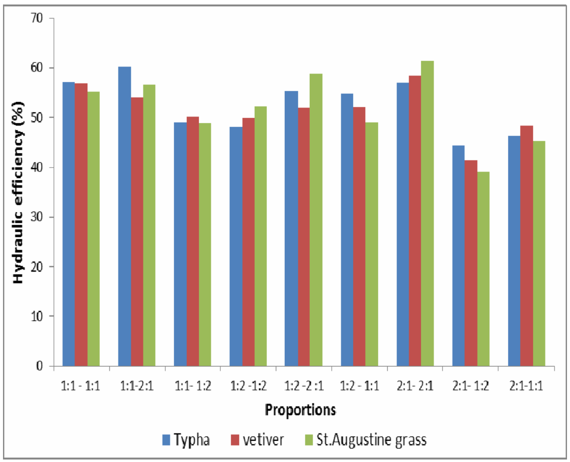

Fig 2. Hydraulic performance of different media and proportions

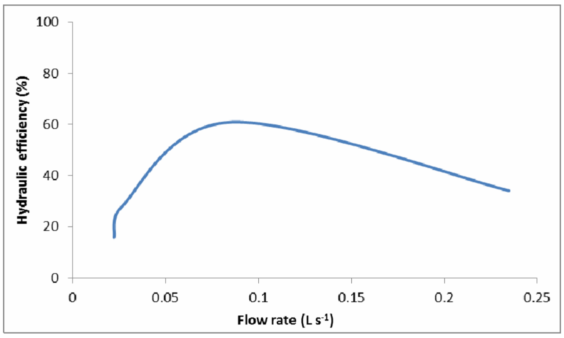

Fig.3. Change in hydraulic efficiency with respect to change in flow rate

Quality improving efficiency was estimated by analysing the inlet and outlet water samples from the dual flow hybrid filter (after 15 days from planting of live filter materials). The average pollutant removal/ normalizing percentages of major physico-chemical parameters in recharge water by the dual flow filter with respect to different media are depicted in Fig. 4.

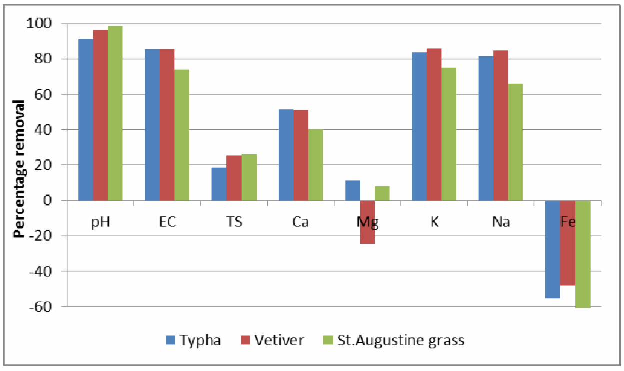

**Fig.4. Average removal/normalizing percentages of major physico-chemical parameters in recharge water by the dual flow filter**

The chemical removal efficiency of recharge dual flow filter (for all media and proportions) was found very high in case of potassium (81.6%) and sodium (77.55%). The pH normalizing efficiency and EC reduction efficiency were also recorded an average value of 95.6% and 81.6%, respectively. The average removal percentage of calcium was moderate, while that of magnesium was very low. The magnesium concentration increased in case of vetiver medium. Substantial increase in the iron content in the effluent water was due to the presence of high iron content in local soils that was used grow live filter medium.

From the overall performance of different media on chemical removal in recharge water, it was concluded that the plant typha was more effective as live filter media. However, for reduction of sediment load (TS), the St. Augustine grass performed better, followed by vetiver. Typha was not found to be very effective in removing sediments. The average TS reduction percentage was also less (23.4%) and this was due to additional soil erosion from the loose filled soil in the outer ring. It was also found that the removal rate of sediments increased after the plants were established fully, which in turn reduced rate of soil detachment. The change of soil structure from loose to compact as the time elapses might have also reduced soil detachment. It was observed that a maximum TS reduction of 68.8% was observed after 60 days of planting the live filter. Poletika *et al*. (2009) could achieve 50-70 % reduction in sediment load by establishing a vegetated filter strip for reducing and filtering runoff. In a study conducted in US, a 1.5 m x 6 m area filter strip of switch grass (*Panicum virgatum*) removed 77 %, while 1.5 m x 3 m filter strip removed 66 % of the incoming sediment from surface runoff (Lee *et al*., 1999). While Hatt *et al*. (2009) reported a reduced mean TSS concentration of 14 mg L-1 in the outlet water after filtering stormwater with a mean TSS load of 128 mg L-1 using a bio filtration system.

The change in the removal rate of TS load, EC and pH with time was studied over a period of 30 days and the results plotted in Fig.5. The quality results of a mature system will be more superior, since it has been demonstrated that biofilters can take some time to reach their optimal nutrient removal performance (Bratieres *et al*., 2008).

The Fig.6 shows the performance of different filter proportions in removing chemicals. It could be observed that the proportion 1:1-1:2 was obviously superior for all live filter media tested.

The Universal performance indices of each filter combinations were determined and subjected to the analysis of variance using SAS software. Based on UPI values, it was observed that that live medium typha plant performed well compared to the other two live media considering the universal performance index values. It is closely followed by vetiver and St. Augustine grass showed the least overall performance. As far as filter proportions are concerned, the ratio 1:1-1:2 showed much superior performance compared to all other proportions.

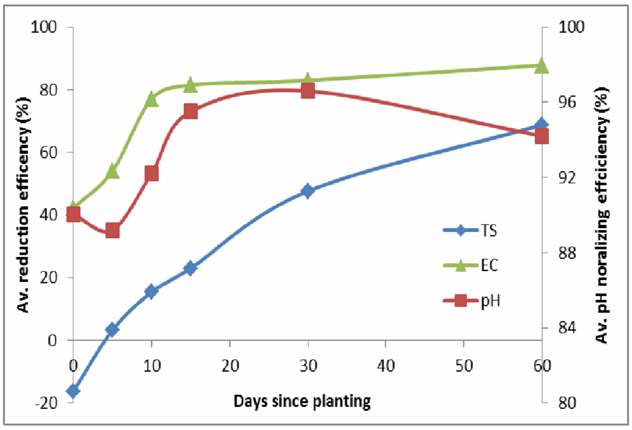

**Fig.5. Change in removal percentage with time for dual flow filter**

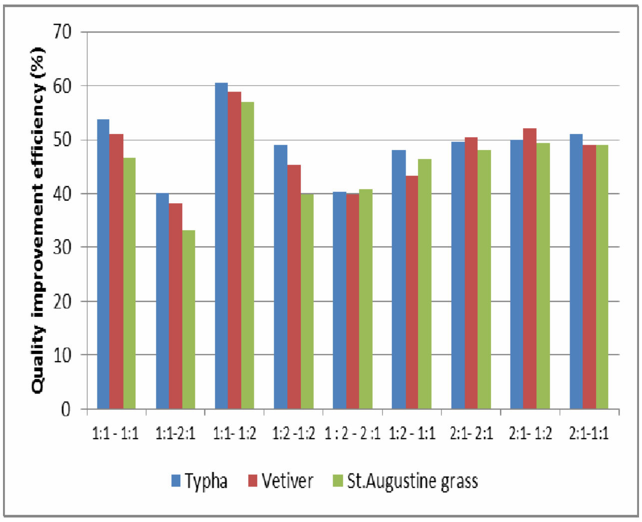

**Fig.6. Quality improving efficiencies with respect to different proportions of dual flow filter**

Benefit cost analysis of the developed filters was carried out to find out its economic feasibility. Fixed and variable costs along with annual returns of the recharge filter were worked out and subsequently the cost of filtration per cubic meter of water, net present value (NPV), internal rate of return (IRR) and benefit-cost ratio (BCR) of the filter were computed as presented in Table 1.

The NPV was observed as positive and IRR was greater than the considered discount rate (14%). Moreover, the BC ratio showed value greater than 1, which is acceptable. These values indicate that establishing such a filter device is highly profitable and an attractive investment proposal. The cost of filtration was as mere as ₹ 0.89 per m3 of stormwater. The developed filtration systems are recommended from an economic point of view being a low cost technology requiring low initial expenditure, zero power need, no maintenance cost and self-dependent operation. They are suitable for areas where there are normal seasonal rains.

**Table 2. The cost of filtration, NPV, IRR and BCR values of recharge filtration systems**

| Type of filter | Recharge |
|---|---|
| Cost of filtration/m3 (₹) | 0.89 |
| NPV (₹) | 3360.75 |
| IRR (%) | 49 |
| BC ratio | 1.15 (1 $= 45 ₹) |

## CONCLUSION

A dual flow filtration mechanism was designed, developed and evaluated for groundwater recharge. The diameters of outer, middle and inner rings were 2.1 m, 1.65 and 1.2 m. The depth of inner ring was 2 m, while that of outer rings were 0.6 m. The dual flow filter showed an increasing trend in hydraulic efficiency with increase in flow rate. The dual flow recharge filter was excellent in normalizing pH, reducing EC and removing K+ and Na+. It performed moderately well for TS and Ca2+ removal and negatively for Fe2+ and Mg2+ removal.

Universal performance indices of each filter combinations were determined and subjected to the analysis of variance. In case of live medium, typha plant performed well followed by vetiver and St. Augustine grass. As far as filter proportions are concerned, the ratio 1:1-1:2 (plant: fibre- pebble: sand) showed much superior performance compared to all other proportions.

Based on the estimated annual costs and returns, all the financial viability criteria (IRR, NPV and BCR) are found favourable and affordable by farmers for investment on developed recharge filtration system. The natural fibre filter media used in this study were cheap, environmentally compatible and biodegradable. The other filter media were also commonly available and renewable in nature.

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