Performance evaluation of filtration unit of groundwater recharge shaft: laboratory study

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The groundwater resource of our country is now under serious threat due to over-exploitation, pollution, industrialization and improper management. The recharge shaft is an efficient and economic method for recharging groundwater. In this study, the effect of variable thickness of coarse sand (CS), gravel (G) and pebble (P) layers of the filtration unit of the recharge shaft on the recharge rate and the sediment concentration of effluent water was evaluated. An experiment was carried out with laboratory-scale models having varying depths of CS, G and P layers in five different thickness combinations, viz. 1 : 1.5 : 3, 1.5 : 1 : 3, 3 : 1 : 1.5, 3 : 1.5 : 1, 1 : 1 : 1 (CS : G : P). These models were operated with six different treatments having varying concentrations of turbid water, similar to the sedimentation level of the surface run-off ranging from 6 to 16 g/l. 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, 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.

Groundwater is an important source for meeting the domestic, agricultural, and industrial water requirements. About 50% of total irrigated area is dependent upon groundwater and about 60% of the irrigated food production depends on irrigation from groundwater wells[1]. Due to over-exploitation of groundwater for different uses and non-implementation of site-specific recharging methods, there is periodic lowering of the groundwater table in major parts of our country[2]. Keeping in view the available artificial and natural recharging techniques, construction of recharge shafts is a plausible low-cost technique, which can be adopted in suitable locations to recharge groundwater from the surface run-off.

In India, there are no fixed criteria for designing the thickness of different layers of the filtration material of the recharge shaft. This leads to uncertainty in achieving adequate recharge rate and avoiding frequent clogging of the filter material due to suspended sediment in the surface waters. To address this research gap, the present investigation was aimed at working out the optimal design of the coarse sand (CS), gravel (G) and pebble (P) layers constituting the filtration beds of the recharge pits, which can lead to higher recharge rate with minimal clogging of the filtration bed. The experiment was conducted by fabrication of laboratory-scale models and subsequent operation of the models with turbid water of varying sediment concentrations. Recharge rate and sediment concentrations under different filtration bed depths were also evaluated in this experimental analysis to arrive at an optimal design of the filtration unit. This design of the filtration unit can also be used for construction of underground storage tanks of rooftop water-harvesting structures.

As envisaged by the Central Ground Water Board (CGWB), the recharge shaft is the most efficient and cost-effective structure that facilitates direct recharge of water to aquifer systems. In view of the research findings related to performances of varying thickness of filtration units, geo-electric resistivity techniques were used to locate potential sites for the construction of recharge shafts in the Indo-Gangetic Plains (IGP) to augment the groundwater recharge[3]. Filtration unit comprising 0.75 m of CS, 1.25 m of G and 2.0 m of P was used. The average recharge rate was observed to be 11.50 and 10.50 l/s during the first and second year of the experiment respectively. The usefulness of a small recharge shaft with filtration bed constructed in the farmer's field at village Bindrala was investigated[4]. The thickness of the CS and G layers of the filtration unit was of equal depth. Overall, there is a lack of laboratory investigations related to the design of filtration units and its operational efficiency.

The filtration unit designed for the laboratory experiment consisted of a circular acrylic casing and a rectangular cubical box along with other fittings for water inflow and outflow. Acrylic pipe of 31 cm outer diameter, 60 cm length and 0.5 cm thickness was used to accommodate the graded filtration materials. A rectangular cubical box with dimensions 33 cm length, 33 cm width and 6.6 cm height was prepared from 0.8 cm-thick acrylic sheets to support the pipe casing and act as a medium for separating the filtration unit from the casing, and facilitate the flow of recharged water through the outlet for subsequent measurements. The experimental set-up with the filtration material contained in the casings with varying ratio (Table 1) of filtration units is shown in Figure 1. The filtration material used in the experimental units, viz. CS (0.2–2 mm), G (6.5 to 19.7 mm) and P (19.7–30 mm) was subjected to mechanical sieve analysis. This was done to screen the uniformly graded materials for use in the filtration units.

The varying sediment concentrations ranging from 6 to 16 g/l were prepared by collecting the surface soil from the experimental farm of the Indian Agricultural Research Institute (IARI), New Delhi, followed by air-drying and sieving the soil with a 0.2 mm IS sieve[5]. The soil particles passing through the 0.2 mm sieve were used as the suspended sediment material for the experiment[6]. Further, the sieved particles were weighted and the sediment concentrations were

Table 1. Experimental design with treatment details and sediment concentration levels

Experiment treatment code	Thickness of filtration layers (CS, G, P; in cm) and ratio (CS : G : P)	Sediment concentration levels for operation of the unit (g/l)	Replications
T1	15, 15, 15 (1 : 1 : 1)	6, 8, 10, 12, 14, 16	3
T2	10, 15, 30 (1 : 1.5 : 3)	6, 8, 10, 12, 14, 16	3
T3	15, 10, 30 (1.5 : 1 : 3)	6, 8, 10, 12, 14, 16	3
T4	30, 15, 10 (3 : 1.5 : 1)	6, 8, 10, 12, 14, 16	3
T5	30, 10, 15 (3 : 1 : 1.5)	6, 8, 10, 12, 14, 16	3

Figure 1. Five experimental units with varying thicknesses of filtration layers.

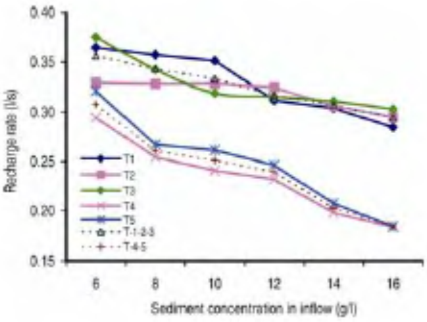

Figure 2. Effect of inflow sediment concentration on the recharge rate for filtration layers of varying thickness.

prepared for the designed levels of 6, 8, 10, 12, 14 and 16 g/l. The design of experiment with treatment details is given in Table 1. The five experimental units were units operated with six different sediment concentration levels with three replications to yield 90 datasets each for recharge rate and sediment concentration values respectively, during experimentation.

It was observed that there was a gradual decrease in the recharge rate with increase in sediment concentration of inflow water. This trend was observed for all the treatment combinations with varying thickness of CS, G and P layers (Figure 2). It can be observed from Figure 2 that the treatment T-4 with CS : G : P ratio of 3 : 1.5 : 1 indicated the lowest recharge rate for all the sediment concentration inflow levels in comparison to the other treatments. Also, T-5 with CS : G : P ratio of 3 : 1 : 1.5 indicated recharge rate slightly more than that of T-4 (CS : G : P ratio of 3 : 1.5 : 1) for all the treatments and all levels of sediment concentration in the recharging water. It was observed that treatments T-1, T-2 (1 : 1.5 : 3) and T-3 (1.5 : 1 : 3) (i.e. T-1-2-3 combination) resulted in higher recharge rates for different levels of sediment concentration in the inflow in comparison to treatments T-4 and T-5 (i.e. T-4-5 combination). The reason for this increase in the recharge rate for the treatments T-1, T-2 and T-3 can be attributed to the lower thickness of the coarse sand layer of the filtration units with changes in the ratio from a minimum of 1 to a maximum of 1.5, and higher thickness proportion of three for the treatments T-4 and T-5. Treatment T-1 (1 : 1 : 1, CS : G : P) resulted in producing the highest recharge with mean of 0.329 l/s for all the inflow sediment concentration levels, followed by T-3 (1.5 : 1 : 3, CS : G : P) with 0.328 l/s and T-2 (1 : 1.5 : 3, CS : G : P) with 0.318 l/s. Also, from treatments T-4 and T-5, it was observed that the higher depths of CS in the filtration unit were significant in reducing the recharge rate of the effluent. Also, the effect of the change in the thickness combination of G and P layers in these two treatments with higher depth of CS was observed to be minimal. Overall, the depth of the CS layer in the filtration unit was responsible for controlling the recharge rate of the effluent. However, the rate of change in the outflow rate was not in proportion with the variations in the depth of the layers of CS, G and P. The best thickness ratio of the filtration unit for obtaining highest flow rate was observed to be 1 : 1 : 1 (CS : G : P).

The trend of the lines for different treatments as shown in Figure 2 indicates that there are two major trends of variation in the outflow rates for different inflow rates of the sediment concentration from 6 to 16 g/l. The outflow rates for the treatment combination T-1-2-3 were clubbed together to produce a trend line as shown in the Figure 2. Similarly, the outflow rates for the treatment combination T-4-5 for varying inflow sediment concentrations were clubbed to generate a trend line as shown in the Figure 2. Regression equations were developed to relate the inflow sediment concentration levels (S_{in}; in g/l) to the observed recharge rate of the effluent (Q_{out}; in l/s) for the treatment combinations T-1-2-3 and T-4-5. The best-fitted regression equations obtained using the first three treatments T-1-2-3 and last two treatments T-4-5 are respectively:

$$Q_{out} = -0.0124 S_{in} + 0.3683 \quad (R^2 = 0.99), \tag{1}$$

$$Q_{out} = -0.0231 S_{in} + 0.3216 \quad (R^2 = 0.96). \tag{2}$$

Sediment concentration (g/l) in the recharged or effluent water was plotted against that of the inflow (g/l; Figure 3). It can be observed from Figure 3 that the sediment concentration in the outflow or recharged water increased with increase in sediment concentration of the recharging water for all treatments with varying depths of the filtration layers. The variation in the sediment concentration of the outflow water was the lowest for treatments T-4 and T-5. There was minimal change in the sediment concentrations of the recharged water (0.35 g/l) for all the treatment combinations with inflow sediment concentration rates of 6 and 8 g/l. But with the increase in the inflow sediment concentration rate from 10 to 16 g/l, there was a considerable difference in the magnitude of sediment

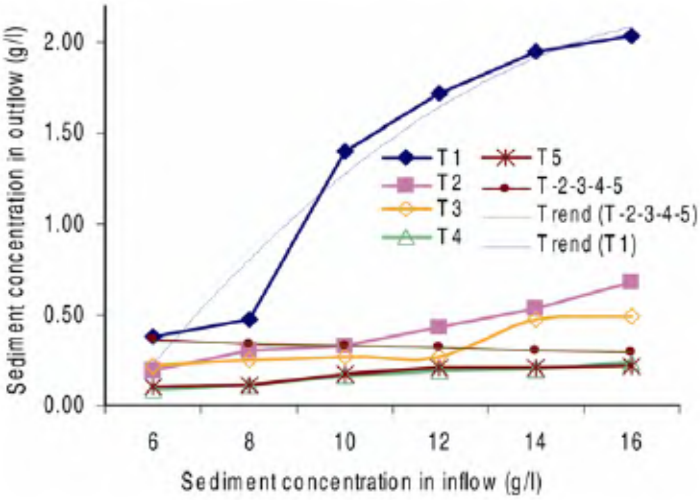

Figure 3. Effect of filtration layer thickness on the sediment concentration of the inflow and outflow water.

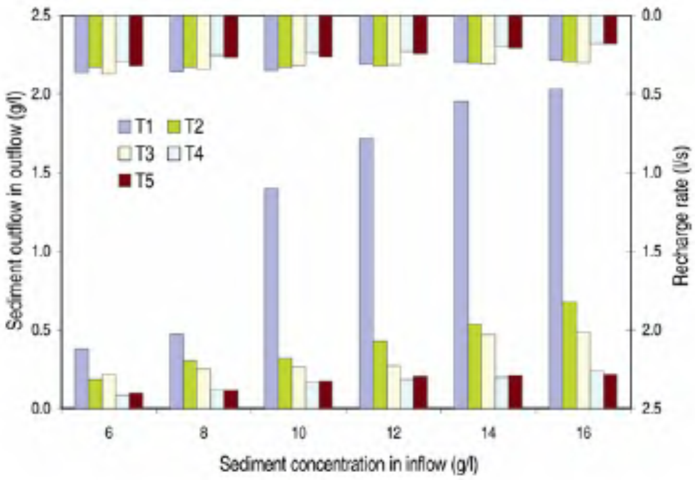

Figure 4. Combined effect of sediment concentration in outflow and outflow rates on the filtration units for different inflow sediment concentrations.

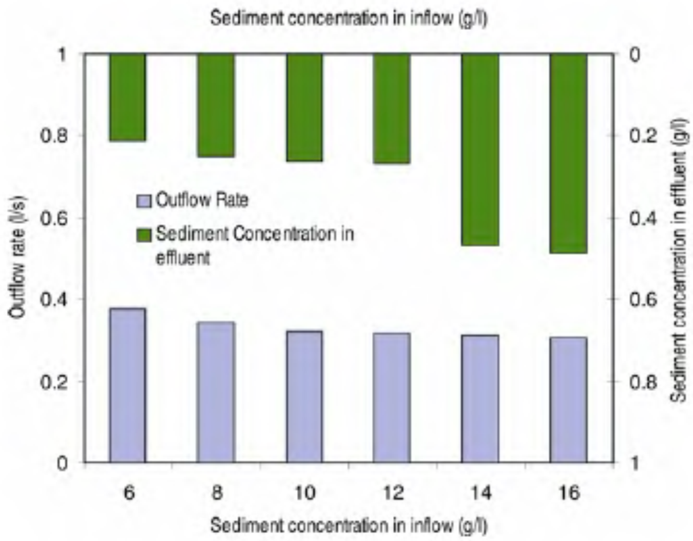

Figure 5. Performance of the filtration unit with optimal thickness ratio 1.5 : 1 : 3 (CS : G : P).

concentration of the filtered water among all the treatments. Moreover, the sediment outflow rates for treatment T-1 (1 : 1 : 1, CS : G : P) was the highest among all treatments. Moreover, treatments T-4 and T-5 resulted in lowest sediment outflow rate, with mean sediment outflow rate of 0.1637 and 0.1695 g/l respectively. Thus, treatment T-4 (3 : 1.5 : 1, CS : G : P) resulted in the lowest sediment outflow rate in comparison with all the other treatments. Further, regression equations were developed using the dataset of inflow sediment concentration (S_{in}; in g/l) and outflow sediment concentration (S_{out}; in g/l) for treatment combinations T-2, T-3, T-4, T-5 and treatment T-1. The best-fitted regression equations for treatments T1 and T-2-3-4-5 are respectively:

$$S_{out} = -0.0505S_{in}^2 + 0.7256S_{in} - 0.4494 \quad (R^2 = 0.94), \tag{3}$$

$$S_{out} = -0.09227S_{in} + 0.0843, \quad (R^2 = 0.97). \tag{4}$$

It is desirable that the filtration unit of the recharge shaft constructed in the field to recharge the groundwater should facilitate recharge of the turbid surface runoff besides adequate filtration to prevent groundwater pollution. On the other hand, optimal design of the filtration unit will aim at a judicious combination of the thickness of the layers of CS, G and P, so as to permit a higher recharge rate and lower sediment outflow rate for a given depth of the surface run-off flowing over the recharge shaft. To arrive at the optimum combination of the filtration layers, the mean of the observed values of the flow rate and the sediment concentration in outflow for all the treatments and replications was plotted in form of a bar diagram (Figure 4). Keeping in view the above criterion in the design of the optimal filtration unit, it can be observed that treatment T-1 resulted in higher flow rate for all the sediment concentration levels, but resulted in higher sediment concentration in the recharged water. Therefore, it cannot be considered as the best treatment to provide an optimal recharge rate and sediment concentration in the recharged water. Again, treatment T-2 resulted in better flow rate but failed to arrest sediment in the filtration unit compared to T-3. Thus, for efficient filtration, though treatment T-5 had an edge over the others, it failed to perform better in the recharge rate for all the sediment concentration levels. Also, treatment T-4 failed to provide better recharge rate in line with that of treatment T-5. Therefore, keeping in view the performance criterion of the filtration unit of the groundwater recharge shaft, the filtration layer thickness ratio of 1.5 : 1 : 3 (CS : G : P) would be considered as the optimal design of the filtration unit of a laboratory-scale model of the recharge shaft. The behaviour of the sediment outflow rate and sediment concentration of the recharged water is presented in Figure 5. It can be observed that the higher sediment concentration in the inflow water resulted in lower recharge rate and reduced the filtration efficiency of all the treatment combinations. However, the rate of reduction in both the recharge rate and the sediment outflow rate was the lowest for the filtration unit with thickness ratio 1.5 : 1 : 3 (CS : G : P). Nonetheless, as an outcome of this laboratory investigation, the filtration unit of groundwater recharge shafts should be designed in the ratio of 1.5 : 1 : 3 (CS : G : P) and tested for its efficacy in recharging groundwater under different real-field situations for its wider applicability and final adoption as a standard design protocol of groundwater recharge shaft.

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Received 29 February 2008; revised accepted 26 December 2008

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