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Performance Evaluation of Filtration System for Groundwater Recharging Well in the Presence of Medium Sand-Mixed Storm Water

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***Abstract*—**Collection of storm water runoff and forcing it into the groundwater is the need of the hour to sustain the ground water table. However, the runoff entraps various types of sediments and other floating objects whose removal are essential to avoid pollution of ground water and blocking of pores of aquifer. However, it requires regular cleaning and maintenance due to problem of clogging. To evaluate the performance of filter system consisting of coarse sand (CS), gravel (G) and pebble (P) layers, a laboratory experiment was conducted in a rectangular column. The effect of variable thickness of CS, G and P layers of the filtration unit of the recharge shaft on the recharge rate and the sediment concentration of effluent water were evaluated.

Medium sand (MS) of three particle sizes, viz. 0.150–0.300 mm (T1), 0.300–0.425 mm (T2) and 0.425–0.600 mm of thickness 25 cm, 30 cm and 35 cm respectively in the top layer of the filter system and having seven influent sediment concentrations of 250–3,000 mg/l were used for experimental study. The performance was evaluated in terms of recharge rates and clogging time. The results indicated that 100 % suspended solids were entrapped in the upper 10 cm layer of MS, the recharge rates declined sharply for influent concentrations of more than 1,000 mg/l. All treatments with higher thickness of MS media indicated recharge rate slightly more than that of all treatment with lower thickness of MS media respectively. The performance of storm water infiltration systems was highly dependent on the formation of a clogging layer at the filter. An empirical relationship has been derived between recharge rates, inflow sediment load, size of MS and thickness of MS with using MLR.

***Keywords*—**Groundwater, medium sand-mixed storm water filter, inflow sediment load.

I. Introduction

GROUNDWATER plays very important role in fulfilling basic demands of drinking needs and food production requirements in many countries. India [7] uses about 80% of drinking water requirements and 60% irrigation demands through ground water resources. Water table is declining at an alarming rate in about 15% of India’s geographical area and threatening the sustainability of agriculture due to escalation in pumping costs, deterioration in groundwater quality and associated socio-economic and environmental factors [3]. As natural groundwater recharging rate is slow hence artificial recharge is an alternative, which has recharging rate exceeding natural condition of replenishment. Any man-made facility that adds water to an aquifer by means of some recharge structure construction (Injection well, recharge cavity and recharge wells), requires recharging water to pass through filter system before final injection to the groundwater system so that entry of physical impurities of the run-off water into the recharge system is prevented. Filter performance is measured by effluent water quality (traditionally, turbidity and suspended solids concentration as well as particle counts and dissolved organic carbon concentration), water production (unit filter run volume) and head-loss development (rate and time to back wash) all of which change over time. In general, filtering systems should be sized using the volume of runoff to be filtered and filtering media selected based upon the pollutants of interest. The filtration unit must perform effectively to get potential benefits from the installed recharge structures [4]. Clogging i.e. decrease in permeability of the filter system by sediments present in recharging water is a major problem in working efficiency of recharging system. Hence, cleaning of filtration system is required at some interval of time by removing upper layer or replacing the whole of the filter medium.

Laboratory and field tests have shown initially the flow-through rates is high but as the filtrate of fine sediments accumulated on its surface, the flow-through rate is diminished. Storm water filters which utilize coarser filter medium such as gravel are susceptible to clogging. It occurs due to the migration of fine sediments through the medium and formation of a layer of low permeability at the bottom of the filter reducing the hydraulic efficiency of the filter [8].

The recharge tube wells performed well during the entire experimental period covering two monsoon seasons without any drastic reduction in recharge rate. An average recharge rate of 10.5 l/s due to individual recharge tube well was observed [5]. The effect of variable thickness of CS, G and P layers of the filtration unit of the recharge shaft on the recharge rate and the sediment concentration of effluent water were evaluated. In a column study of 60 cm length and 31 cm diameter, provision of CS, G and P in the ratio 1.5 : 1 : 3, i.e. 15 : 10 : 30 cm was found to be most efficient in filtration unit for a recharge shaft [1], [9]. Removal is different at the various depths of the filter with the influent particle concentration being reduced dramatically in the top section of the filter and smaller reductions occurring near the bottom of the filter. Therefore, removal efficiency in the larger media improves

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substantially compared to the smaller media at each successive depth of the filter [2].

The particle size of MS therefore, plays an important role but it is not standardized. This leads to uncertainty in achieving adequate recharge rates and frequent clogging of the filter.

Finer medium system such as medium sand (MS) also gets clogged at the top of filter but it can be conveniently scrapped-off and managed [6]. The aim of this laboratory experiment is to evaluate the filtration efficiency of MS as the top layer of the filter medium in groundwater recharge wells and its effect on the quantity of recharged water. Laboratory study was conducted under constant head condition because it was difficult to analyse the impact of a large number of treatments involving different media size, different thickness of media and sediment load of influent water on clogging, recharge rate and sediment penetration under actual field conditions.

II. Method

A. Experimental Setup

A laboratory experiment was conducted in a rectangular column of (B×W×H) 20×16×120 cm and having provision of regulated water inflow and free outflow as shown in Fig. 1.

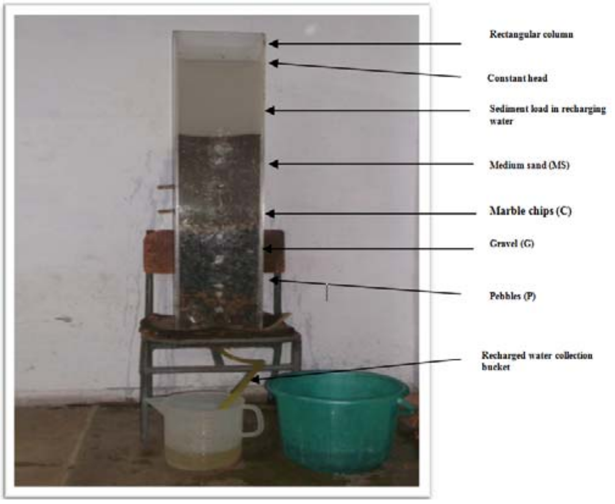

Fig. 1 Experimental column used in the laboratory study

TABLE I
FILTERING MATERIAL SIZES TO SUPPORT MEDIUM SAND BED FOR COLUMN STUDY

Medium Sand (MS)		Thickness of Chip (cm)	Gravel (G)		Pebbles (P)		Results
Dia. (mm)	Thickness (cm)		Dia. (mm)	Thickness (cm)	Dia. (mm)	Thickness (cm)	
0.150-0.300	25	0	0.8-2.0	25	2-4	20	Sand Passed
0.150-0.300	25	3	0.8-2.0	22	2-4	20	Successful to Support MS bed

TABLE II
EXPERIMENTAL DESIGN AND SEDIMENT CONCENTRATION LEVEL

Treatment	Size of MS Treatment Dia (mm)	Mean diameter (mm)	Thickness of bed (cm)	Sediment concentration (mg/l)	Replications
T1	0.150-0.300	0.212	70	250,…., 3000	3
T2	0.300-0.425	0.357	75	500,….,3000	3
T3	0.425-0.600	0.505	80	500,…..,3000	3

*Gravel size (0.8-2 cm dia.) and thickness (22 cm), marble chips (0.475-0.8 cm dia., 3 cm thickness) and boulders size (2-4 cm dia.) and thickness (20 cm) were constant for all treatment combinations.

Inlet was provided in the upper portion of the column to maintain a constant hydraulic head manually during the test run. Outlet was provided at the bottom of column to drain out filtrate water. One concentric gallon was provided at the bottom of the column in such a way that only the flow-through water was collected in the gallons. The filtrate collected in the gallon only was utilized for further analysis. A series of initial experiments, using tap water and gravel and boulders of different sizes and thickness as supportive layers for MS at the top (Table I), were conducted to finalize these parameters for further studies. Gravel (8–20 mm diameter, 22 cm thickness), marble chips (0.475-0.8 cm diameter, 3 cm thickness) and boulders (20–40 mm diameter and 20 cm thickness) were used as supportive layers below MS in subsequent studies involving treatments of MS and sediment load of inflow water (Table II). Marble chips of thickness of 3 cm were placed above gravel layer. It is seen from Table II that studies were conducted using MS of three sizes and involving: estimating recharge rates and clogging time and removal efficiency. In the set of studies aimed to evaluate recharge and clogging time, the thickness of MS was kept equal to the thickness estimated by empirical models developed in this study corresponding to the highest sediment load encountered in real field conditions.

The synthetic water of different sediment loads was prepared using the fine sand. This was done to ensure that the physical characteristic was truly representative of the storm water run-off. It was observed that the first storm generated more sediment in run-off water than the succeeding ones. Sediment load up to 2,560 mg/l in run-off water was also reported in Punjab soils [10]. Considering the above, synthetic water for the laboratory tests was prepared with sediment load of 250–3,000 mg/l using dried fine sand sieved through 0.150 mm sieve. Experiment runs were performed with sediment load of 250, 500, 1,000, 1,500, 2,000, 2,500 and 3,000 mg/l and replicated three times. The synthetic water of different sediment loads was introduced in the column through a rectangular column covered with cloth net to dissipate the impact of inflow water and to minimize the displacement of MS particles. Clean tap water was passed through filtering medium for 10 min before each experiment run to drain any soluble materials.

B. Analysis

The experiments studies [11] show that the recharge rate by MS filter media is dependent on the suspended solids from influent recharge water. The percent removal of solids increased as the recharge rate decreased.

In the filtration mode of operation, water containing suspended solids is applied to the surface of the filter media. The sand rapidly collected suspended solids and soon clogged. Clogging may be defined as a buildup of head loss (pressure drop) across the filter media until it reaches some predetermined design limit. A filter is usually operated until just before clogging.

The time taken after the starting of experiment to when the recharging rate became constant is considered as clogging time.

III. Results and Discussion

Laboratory experiments are performed to evaluate the relationship among recharge rate, particle size of the medium, sediment load of inflow water and efficiency of medium sand mixed storm water rectangular filtration system. Results of the experiment are discussed below.

A. Estimation of Recharge Rate and Clogging Time Using Graph

Variation in average recharge rate of different MS beds and different thickness of beds corresponding to varying sediment loads of inflow water during test run of 30 min was ploted and regression equations were developed to relate the inflow sediment loads to the observed recharge rate of the effluent for the all treatment. The best-fitted regression equations obtained in 80 cm of thickness of filter bed for all treatments. The following empirical relationships were derived between recharge rates (Q) and inflow sediment load (S) for T1, T2 and T3 with varying thickness of filter bed.

a) 70 cm of Thickness of Bed

$$Q = -9 \times 10^{-11} S^3 + 6 \times 10^{-7} S^2 - 0.001\, S + 5.545, \quad R^2 = 0.992 \text{ for T3} \tag{1a}$$

$$Q = -7 \times 10^{-11} S^3 + 4 \times 10^{-7} S^2 - 0.001\, S + 4.036, \quad R^2 = 0.987 \text{ for T2} \tag{1b}$$

$$Q = -7 \times 10^{-12} S^3 + 1 \times 10^{-8} S^2 - 3 \times 10^{-5}\, S + 1.573, \quad R^2 = 0.994 \text{ for T1} \tag{1c}$$

b) 75 cm of Thickness of Bed

$$Q = 2 \times 10^{-11} S^3 + 2 \times 10^{-8} S^2 + 6.069, \quad R^2 = 0.999 \text{ for T3} \tag{2a}$$

$$Q = 1 \times 10^{-11} S^3 - 5 \times 10^{-8} S^2 - 8 \times 10^{-5}\, S + 3.942, \quad R^2 = 0.997 \text{ for T2} \tag{2b}$$

$$Q = -6 \times 10^{-13} S^3 - 1 \times 10^{-9} S^2 - 3 \times 10^{-5}\, S + 1.885, \quad R^2 = 0.989 \text{ for T1} \tag{2c}$$

c) 80 cm of Thickness of Bed

$$Q = 7 \times 10^{-12} S^3 + 3 \times 10^{-10} S^2 + 6.204, \quad R^2 = 0.990 \text{ for T3} \tag{3a}$$

$$Q = -6 \times 10^{-11} S^3 + 4 \times 10^{-7} S^2 + 4.117, \quad R^2 = 0.992 \text{ for T2} \tag{3b}$$

$$Q = -1 \times 10^{-11} S^3 + 6 \times 10^{-8} S^2 + 2.136, \quad R^2 = 0.998 \text{ for T1} \tag{3c}$$

It was observed that there was a gradual decrease in the recharge rate with increase in sediment load of inflow water. A sharp decline in recharge rate at higher sediment loads was observed in all three MS beds due to immediate blocking of flow pathways of the recharging water. The recharge rate at 250 ppm turbidity level was almost constant throughout the all experiment duration. At 500 ppm level, the recharge rate was constant initially for some time after which it decreased rapidly to reach the minimum level within a few minutes. This occurred due to entrapment of initially suspended particles in the pores followed by accumulation of the suspended particles on the top of the bed in the form of a clogging layer, which drastically reduces the recharge rate.

It can be observed from plot between recharge rate and sediment load that the treatment T1 with all varying thickness of MS media indicated the lowest recharge rate for all the sediment load inflow levels in comparison to the other treatments. Also, T2 with all varying thickness of MS media indicated recharge rate slightly more than that of T1 for all the treatments and all levels of sediment load in the recharging water. It was observed that all treatments T3 with varying thickness resulted in higher recharge rates for different levels of sediment load in the inflow in comparison to treatments T1 and T2. The reason for this increase in the recharge rate for the treatments T3 can be attributed to the intrinsic pores of the medium sand layer of the filtration unit comparison to treatment T2 and T1.

However, the difference in recharge rates of T1, T2 and T3 gradually decreased with increase in sediment load of the inflow water. Higher sediment load (1,500 ppm or more) reduced recharge rate drastically in MS bed T3, probably due to a rapid blocking of intrinsic pores with higher load of suspended particulates. The higher recharge rate in T3 through larger intrinsic pore size resulted in higher permeability of the medium as well as to lower removal efficiency and consequently less clogging of the top layers.

Treatments T1, T2 and T3 with thickness 75 cm of MS media indicated recharge rate slightly more than that of T1, T2 and T3 with thickness 70 cm of MS media respectively. Treatments T1, T2 and T3 with thickness 80 cm of MS media indicated recharge rate slightly more than that of T1, T2 and T3 with thickness 75 cm of MS media respectively. The reason for this increase in recharge rate for the T3 can be attributed to lower head loss with increase thickness of MS filter media. Treatment T3 resulted in producing the highest recharge with average of 4.0 lpm, 4.80 lpm and 5.20 lpm for all the inflow sediment load levels during experiment run of 30 min with thickness of 70 cm, 75 cm and 80 cm respectively. Overall, the thickness of the MS 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 thickness of the layers of MS. These results suggest that the performance of MS beds in the field can be improved by making some provision to reduce higher sediment load of inflow water to a lower level before it approaches the filter bed.

B. Using Multiple Linear Regression analysis (MLR)

The following empirical relationships has been derived between recharge rates (Q in lpm), inflow sediment load (S in ppm), size of medium sand (D in mm) and thickness of medium sand (T in cm). The relationship obtained is given below as (4)

$$Q = -1.837 \times 10^{-04} \times S + 11.242 \times D + 7.817 \times 10^{-02} \times T - 2.589 \quad (4)$$

The R^2 for best-fitted curve obtained is 0.973 and Correlation coefficient obtained is 0.987. For the experiment data, seven varying influent of sediment load (ppm), three varying size of MS and three varying thickness of MS are used to derived the relationship between them. The observed and predicted recharge rate by MLR is shown in Fig. 2.

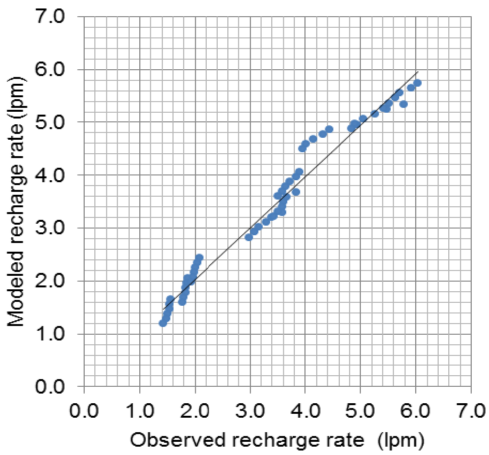

Fig. 2 Observed and modeled recharge rate using MLR

C. Using Artificial Neural Network (ANN)

The above relationship between recharge rates (Q in lpm), inflow sediment load (S in ppm), size of medium sand (D in mm) and thickness of medium sand (T in cm) has been also tried by using neural network. The neural network analysis has been carried out using 10 fold cross validation. The correlation coefficient obtained is 0.993 and root mean squared error is 0.1672. The R^2 obtained by ANN is 0.986 which is better than as obtained in MLR. The model parameters selected for ANN are hidden layer = ‘a’ where 'a' = (attribs + classes)/2, learning rate =0.3, momentum = 0.2 & no of seed = 500.

IV. Conclusions

From the experiment carried out the following conclusions are obtained.

- The recharge rates through all MS beds were substantially high at inflow concentrations of 1,000 ppm or less. A sharp decline in recharge rate was observed at higher sediment concentrations of all sizes due to quick clogging of flow pathways of recharging water. These results suggest that the performance of MS beds in the field can be improved by making some provision to reduce higher sediment load of inflow water to a lower level before it approaches the filter bed.
- All treatments with higher thickness of MS media indicated that the recharge rate is slightly more than that of treatments with lower thickness of MS media.
- 100% of the suspended solids were entrapped in the top 10 cm layer of MS, the level of accumulation in the upper layer increased with increasing turbidity of influent water.
- Empirical relationship is also generated by using multiple linear regressions (MLR). The R^2 obtained is 0.973, Correlation coefficient obtained is 0.987.
- Relationship is generated by using artificial neural network (ANN). The value of R^2, Correlation coefficient and root mean squared error are 0.986, 0.993 and 0.1672 respectively.

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