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ICAR - Indian Institute of Soil and Water Conservation (IISWC)
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Foreword

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Dr M. Madhu
Director

The easy accessibility of groundwater by even small-scale users, its local availability, and difficulty of coordinating and governing many users of the same aquifer across wide geographic spaces has frequently lead to indiscriminate extraction of this precious natural resource for domestic, industrial, and agricultural uses around the world. Groundwater exploitation, particularly in India, has increased by leaps and bounds over the last 50 years along with the expansion of shallow, mostly private wells. At the same time changes in the hydrologic regimes, in particular, the growing scarcity of surface water supplies as agricultural and other users have expanded; have pushed water users to seek groundwater alternatives. The natural recharge studies carried out over different hard rock terrain indicated that only 5-10% of the seasonal rainfall recharges the groundwater. The meager annual replenishment of natural recharge to groundwater alone with multiple uses may not be able to meet the projected water demand of 17,000 million cubic meters per year by 2050. To respond to the growing groundwater crisis and take advantage of the high levels of runoff not captured by natural recharge, augmenting groundwater resources through artificial recharge of aquifers has become widespread in India over the last decade.

ICAR-Indian Institute of Soil and Water Conservation, Research Centre, Vasad located in Anand district of Gujarat has developed a sand-based runoff filter to capture the runoff from farmer's fields for artificial groundwater recharge. The runoff harvesting and its recycling through groundwater recharge is the flagship technology of the circular economy. This technical bulletin is prepared based on the knowledge generated and data collected from the institute sponsored research and development project entitled "Field evaluation of groundwater recharge filters developed by ICAR-IISWC, Vasad". The different designs developed and previously tested as laboratory-scale models were constructed in farmer's field for studying the hydraulics and generate appropriate recommendations under different field and hydrologic conditions. This bulletin provides detailed information on design, execution, and hydraulics of runoff filters. I hope this bulletin will be useful to scientists, academicians, and officials of Gujarat government working under State Watershed Management Agency (GSWMA), Gujarat Water Resource Department, Water and Land Management Institute (WALMI), Agriculture Department, Forest Department, Krishi Vigyan Kendra, and other user non-government agencies for implementation of runoff harvesting and its recycling through artificial groundwater recharge/augmentation through various schemes.

September, 2021
Dehradun

(M. Madhu)


भारतीय मृदा एवं जल संरक्षण संस्थान
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माता भूमिः पुत्रो अहं पृथिव्याः। पर्जन्यः पिता स उनः पिपर्तु ।।

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The authors are indebted to Dr V.N. Sharda, Chairman RAC, Member ASRB, and Former Director, ICAR-IISWC, Dehradun who in fact had been the source of inspiration for conceiving, planning, getting it through, and then successfully executing this important research and development project at various locations in Gujarat. Authors are also very much thankful to Dr P.K. Mishra, Former Director, ICAR-IISWC, Dehradun, Dr S.K. Chaudhari, DDG (NRM), ICAR, Dr Trilochan Mohapatra, Secretary (DARE) & Director General (ICAR) for providing financial assistance for the implementation of this research project. We are also thankful to Director, ICAR-IISWC, Dehradun for providing financial assistance for publishing this bulletin.

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(Authors)


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Contents


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1.0 Introduction

A large number of open/bore wells have turned defunct due to overexploitation of groundwater and poor well maintenance. In India, the groundwater level is depleting at the rate of 10-25 cm per year (Tripathi, 2018) and the net annual groundwater availability is estimated to be 398 billion cubic meter (Suhag, 2016). With shrinking recharge surfaces and increased pressure on groundwater, artificial recharge is becoming an important component of watershed programs under semi-arid conditions. The incongruity between groundwater withdrawal and natural groundwater recharge is symbolic of a predicament condition leaving a large number of the wells redundant in India (Biswas *et. al.*, 2017). The declining groundwater level due to overexploitation permits imperative deterrent measures such as the implementation of improved water-saving technologies, recharge associated extraction policies, and promoting community-based aquifer management practices (National Water Policy, 2012). The direct well recharge using defunct and dried wells is one of the best options for quicker augmentation of groundwater as it entails less land, curtails evaporation losses, and cost of artificial groundwater recharge. The agriculture sector devours nearly 60% of the total groundwater resources mined and is extensively dependent on it for irrigation needs (Gandhi and Namboodiri, 2009). Further, decentralized groundwater recharge in the central part of India often thrives on the practice of diverting excess runoff from agricultural landscapes to the wells, posing a serious threat to groundwater quality and eventual sealing of wells and aquifer pores (Edward *et. al.*, 2016). Therefore, runoff filter is economically viable in areas having a confined aquifer system with poor natural recharge due to existing lithological formation below the root zone of the crops. The seasonal runoff generated from the farmers' field, seasonal gullies, unlined canal beds, runoff collected in low-lying areas/natural depression, runoff generated from urban areas such as roadsides, pavement, and highways can be suitably diverted for artificial groundwater recharge. There are several studies on groundwater augmentation by diverting excess runoff from farmer's fields, employing traditional sand and gravel-based filters to capture sediments and other impurities in the runoff (Nassar and Hajjaj, 2013). In these variations, the treated runoff was either discharged to the storm drainage system or, directly to the surface water bodies, whilst providing sufficient space and opportunity time for the surface runoff to pass through the filter media. The filtration process is a complicated correlation between filtration efficiency and filtration rate that necessitates further research studies (Segismundo *et. al.*, 2017). The prolonged filtration time against improved filtration efficiency prompts the risk of damage to the standing crop due to water logging in the crop field (Hashimoto *et. al.*, 2019). The inadequate filtration leads to endangering groundwater contamination. The runoff generated from the agricultural land contains higher sediment in suspension due to frequent soil disturbances in cultivation practices (Kurothe *et. al.*, 2014) rendering the filter media susceptible to clogging (Le Coustumer and Barraud, 2007). These principal issues as perception motivated the present study, in which field-scale experiments were carried for evaluation of the hydraulic performance of runoff filters. The generated information on the hydraulic performance of runoff filter was employed in decision making on design dimensions of the recharge filter for peak recharge rate, sediment trap efficiency, frequency of maintenance, and effective life in different field hydrologic conditions.

2.0 Design Criteria for Sand-Based Runoff Filters

2.1 Design runoff for filter

The runoff estimation for the design of runoff filters was carried out using the USDA SCS-Curve Number method and the Weibull method was used to find out the design runoff at 80% probability for the semi-arid regions of Central Gujarat.

$$Q = \frac{(P-I_a)}{(P-I_a)+S}$$

$$S = \frac{25400}{CN} - 254$$

Where Q is runoff in mm, P is daily rainfall in mm, I_a is initial abstraction during the period between the beginning of rainfall and runoff in equivalent depth over the watershed in, mm (I_a=0.2S), S is potential maximum retention after which runoff begins in mm, CN is the standard curve number which is determined based on land use, hydrological soil group and antecedent moisture condition.

2.2 Weibull distribution

The runoff estimated for different years was arranged in descending order and a rank was assigned to the arranged data, then probability was obtained using the equation given below.

$$P\ (X \geq x_m) = \frac{m}{n+1}$$

Where P is the probability at X which should be greater than x_m, m is rank and n is the number of years.

2.3 Estimation of peak rate for runoff filter

The peak runoff rate was computed using rational formula.

$$Q_p = \frac{CIA}{360}$$

Where Q_p is Peak runoff rate ($m^3 s^{-1}$), C is runoff coefficient (values ranging from zero to one), I is the rainfall intensity for a design frequency and duration equal to the time of concentration ($mm\ hr^{-1}$), A is the area of the watershed (ha). The time of concentration for overland flow was computed using the Kerby method for overland flow (Kerby, 1959).

$$T_C = 1.44 \times \left(\frac{L_o n}{S^{0.5}}\right)^{0.467}$$

Where T_c is the time of concentration in minutes, L_o is the length of the overland flow (m), n is the roughness coefficient, and S is the slope fraction ($m\ m^{-1}$).

2.4 Mechanical sieve analysis of filter materials

The selection of suitable material for the construction of runoff filters should be based on a gradation curve using mechanical analysis of different sizes of available filter materials. The material should be arranged in ascending order of their sizes, viz. fine size material on the top and coarse size material at the bottom of the runoff filter. The two criteria of permeability and stability of the filter layer require to be contended. The design criteria were developed by the U.S. Bureau of Reclamation (Winger and Ryan, 1970) and the USDA Soil Conservation Service (SCS, 1988). The design criterion for permeability of the filter is given below:

$$\frac{50\ percent\ size\ of\ filter}{50\ percent\ size\ of\ base} = 12\ to\ 58$$

$$\frac{15\ percent\ fine\ size\ of\ filter}{15\ percent\ fine\ size\ of\ base} = 12\ to\ 40$$

In the case of the uniformly graded filter and base material (i.e. material is lacking the excess presence of certain particle sizes), a filter stability criteria ratio of less than 5 is generally considered as safe.

$$\frac{15\ percent\ size\ of\ filter}{85\ percent\ size\ of\ base} = less\ than\ 5$$

3.0 Laws Governing Hydraulics of Runoff Filters

The recharge rate through the filter is governed by Darcy's law. The hydraulic properties of the top layer of the runoff filter having finer material *i.e.* sand govern the recharge rate. The particle size and its distribution, permeability of the sand layer, the surface area of the sand layer, the thickness of the sand layer, and the head of runoff over the top surface govern the recharge rate and sediment trap efficiency through runoff filters. The other coarser layers beneath the finer material layer just provide the support required to hold the finer layer. The main filtering of runoff is carried out by the top finer layer. The filtered runoff can suitably be conveyed through PVC pipes of appropriate carrying capacity to recharge the dug wells/tube wells.

4.0 Optimal Thickness of the Filter Layers

The optimal design of runoff filters with three layers of Coarse Sand (CS) with particle size distributed between 0.2-2 mm, Gravel (G) with particle size distributed between 6.5-19.7 mm, and Pebbles (P) with particle size distributed between 19.7-30 mm should have a thickness of each layer in the ratio of 1.5: 1 : 3 (CS: G : P).

The additional layers of charcoal and potassium permanganate ($KMnO_4$) or other suitable chemical treatment is required to remove the microbiological contamination to make it suitable for drinking purpose. However, there is no need for these layers if the recharged water is to be used for irrigation purposes only.

5.0 Measurement of the Hydraulic Performance of Runoff Filters

5.1 Measurement of recharge rate

The hydraulic head of runoff standing above the runoff filter was measured using the stage level recorder installed in the farmer's field. The recharge rate leaving from the runoff filter was measured by 90° V-notch, which is made of a galvanized iron sheet of 1.5 mm thickness along with a stage level recorder. The runoff charts obtained from the stage level recorder were digitized using surfer software to compute the recharge rate of the runoff filter with time for a particular rainfall event.

$$Q = 4.28 \times C \times \tan\left(\frac{\theta}{2}\right) \times (h+k)^{\frac{5}{2}}$$

Where Q is discharge rate in m^3/s, C is discharge coefficient, θ is the notch angle, h is head of water over V- notch (m), k is the correction factor.

5.2 Measurement of sediment trap efficiency

The runoff samples entering and leaving the runoff filters were manually collected on the downstream side of V-notch for assessing the sediment trap efficiency of the runoff filters. The runoff samples were dried in the oven and weighed in the physical balance. The sediment per unit of runoff was multiplied with total runoff generated during a particular rainfall event to calculate the sediment at the inlet and outlet of the runoff filter to get sediment trap efficiency.

$$STE = \left(1 - \frac{S_o}{S_i}\right) \times 100$$

Where STE is sediment trap efficiency (%), S_o is sediment concentration at the outlet of the runoff filter (g/l), S_i is sediment concentration at the inlet of the runoff filter (g/l).

6.0 Economics of Runoff Filters

6.1 Valuation of groundwater augmented through runoff filters

The residual method was used to estimate the annual value of groundwater used. This method suits better in agricultural production where the production process is standardized, simple, and stable over time and the irrigation water has a significant contribution to the value of output. This gives an average value of groundwater used for irrigation. The average value of the resource determines if it is justified to invest in runoff filters to augment artificial groundwater recharge for irrigation. The non-water production costs were subtracted from total revenue to obtain the residual revenue. This was divided by the quantity of irrigation water used in the production of crops. The average value of wells' discharge was taken from the average discharge of exploratory wells of different depths reported in the published groundwater brochure of the Central Ground Water Board (CGWB) for the Gujarat region.

The economic analysis was done with assumptions that the groundwater recharged through runoff filters was largely used in agricultural production and farmers own the infrastructure such as well and motor pumps. The annual return to groundwater use was estimated as the residual value of groundwater use divided by the total groundwater used in crop production (□/m^3). The cost of groundwater use (□/m^3) was estimated as the sum of the annualized capital cost of runoff filter construction, annual maintenance cost, and the operational cost, *i.e.* annual energy cost of running pump divided by the volume of annual recharge from runoff filters.

6.2 Groundwater abstraction costs

The total cost of abstraction was calculated in two parts.

$$Total\ Cost = Capital\ Cost\ + Operational\ Cost$$

The capital costs included the cost of constructing a runoff filter, which was annualized over the life of the well (10 years) using a discount rate (7%). Operational costs were calculated based on energy needed to pump groundwater which was determined by the combination of groundwater table depth, fuel prices (electricity charges), and capacity of the pump (7.5 HP). To this annual maintenance and repairs were added to get annual operational costs. Annualized capital costs were added to operational costs which were then divided by total water abstracted to get groundwater abstraction cost.

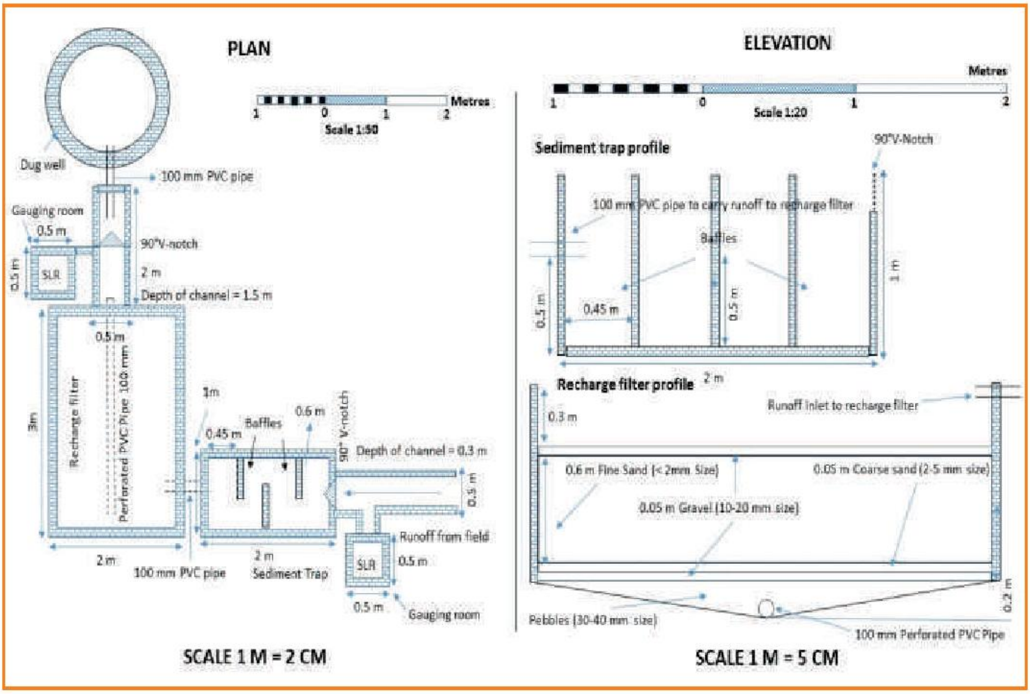


Fig. 1: Design of downward flow runoff filter

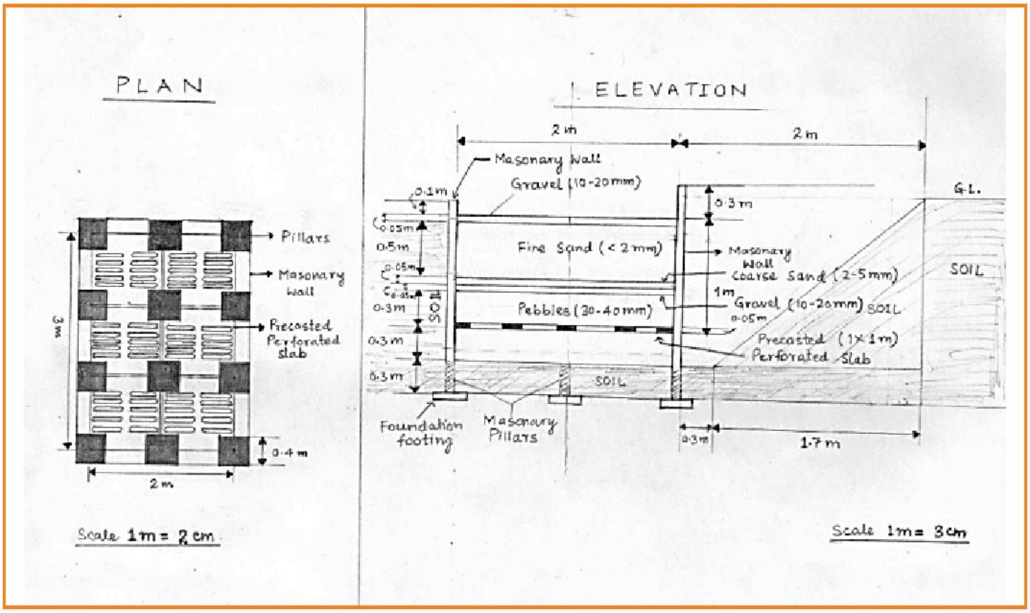


Fig. 2: Design of upward flow runoff filter

Fig. 3: Downward flow runoff filter in the farmers' field

Fig. 4: Improved upward flow runoff filter in the farmers' field

Fig. 5: Status of the water table in the open well before the implementation of runoff filter

Fig. 6: Status of the water table in the open well after installation of runoff filter

7.0 Why Runoff Filters for Augmenting Groundwater Recharge

The natural groundwater recharge in the Central Gujarat region accounts for about 8% of the annual rainfall of 700 to 800 mm (Sharda *et. al.*, 2006). The agricultural land parcels in the region are fairly big and are capable of producing adequate storm runoff to have a visible effect on groundwater augmentation (Kurothe *et. al.*, 2012). However, with the bigger stretch of the land, the runoff also carries a huge load of sediments in suspension. A case study on surface water quality (Kumar and Sena, 2011) was carried out with the samples collected at the outlets of four different agricultural catchments having an area of 0.4 to 0.9 ha from the Vejalpura-Rampura watershed in Kheda district of Central Gujarat, India.

The samples were analyzed for potential impurities such as inorganic and organic constituents; those could be potentially detrimental to groundwater. An objective comparison to water samples collected from 40 wells revealed the relatively lower content of $CO3^{2-}$, HCO^{3-} , Cl^{-} , $SO4^{2-}$, Ca^{2+}, Mg^{2+}, Na^{+} in runoff samples than those from the groundwater (Kurothe *et. al.*, 2012). Further, with no trace of heavy metals measured in the runoff, and the least possibility of heavy metals in absence of any potential sites nearby, scoping to target the runoff filtration was limited to the suspended sediment only.

8.0 Hydrologic Design of Runoff Filter

The runoff filters were designed for 0.4 ha farm size, which is usually available with most of the farmers in the semi-arid regions of Gujarat. The design runoff for the runoff filter design was estimated using USDA SCS-CN method, the standard curve number was assumed (67) for cultivated crop field with bunds under hydrologic soil group B, dominated by sandy-loam soil having moderate soil infiltration characteristics. The last 30 years of rainfall data were analyzed for the estimated design runoff at 80% probability as 125 mm.

9.0 Hydraulic Design of Runoff Filter

The optimum size of the runoff filter was found to be 6 m^2 to handle the peak runoff available at the inlet of the runoff filter, with provisions to divert excess runoff in case of an extraordinary event. The material used in the construction of runoff filter layers was based on a particle size gradation curve of the filter materials obtained using wet sieve mechanical analysis in Yoder's apparatus in the soil laboratory. The filter material was arranged in ascending order of their sizes, *viz.* fine size material on the top and coarse size material at the bottom of the runoff filter. The two essential criteria of permeability and stability of filter layer were contented in the optimal design of filters with three layers of Coarse Sand CS (0.2-2 mm), Gravel G (6.5-19.7 mm), and Pebbles P (19.7-30 mm) having a thickness of layers in the ratio of 1.5: 1: 3 (CS: G: P), respectively. The thickness of the filter layer was kept uniform in both the designs of the groundwater recharge filter i.e. Coarse Sand layer (0.3 m), Gravel (0.2 m), and Pebbles (0.6 m) with a total thickness of 1.1 m of the filter. The equivalent hydraulic permeability of the filter was found to be 2.56×10^{-3} m/s. The hydraulic head of water in the recharge filter was fixed at 30 cm, considering the height of the bund usually constructed by the farmers in their field. The cross-section, thickness of the different layers of the filter, the hydraulic head was kept uniform in both the runoff filter designs. The downward flow and upward flow runoff filter plan and elevation are shown in Fig. 1 and Fig. 2. The mechanical sieve analysis of the sediment samples collected from the runoff water and filter layers was carried out to fulfill the two important criteria of permeability and stability as shown in Fig. 7. The permeability criterion for runoff filter design was found to be 16.42, which was within the range *i.e.* 12 to 40. The stability criterion of the runoff filter design was found to be 1.09, which was less than 5 as shown in Fig. 8.

10.0 Hydraulic Performance Parameters

The hydraulic parameters of both the designs were evaluated, based on performance parameters of peak recharge rate, sediment trap efficiency, and frequency of maintenance and useful working life. The conventional downward flow and improved upward flow designs were constructed in the farmer's field as shown in Fig. 3 and Fig. 4, respectively, and evaluated during the year 2017 to 2019. The status of the water table in the open well before implementation and after installation of runoff filter in the farmer's field is given in Fig.5 and Fig.6, respectively. The downward flow design differs from the upward flow design of the runoff filter in the concept of the flow direction of runoff. Similar provisions were incorporated in the sediment trap of both the designs of runoff filters to retain the maximum sediment before the entry of runoff in the filter. In the downward flow runoff filter, the runoff enters through the top sand layer of the filter; however, in the upward flow runoff filter the runoff enters the filter from the bottom through the pebbles layer of the runoff filter.

Fig. 7: Mechanical sieve analysis of filter materials for permeability and stability analysis of runoff filter

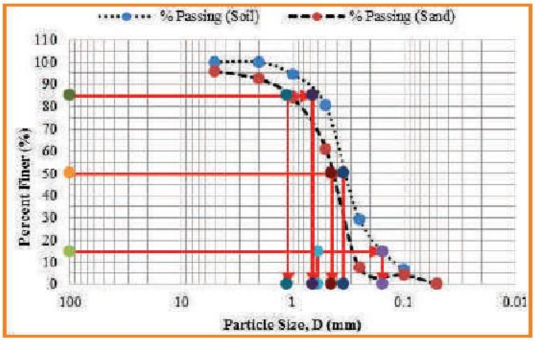


Fig. 8: Particle size distribution curve of sand used as filter media and sediments collected from runoff samples from the farmers' field

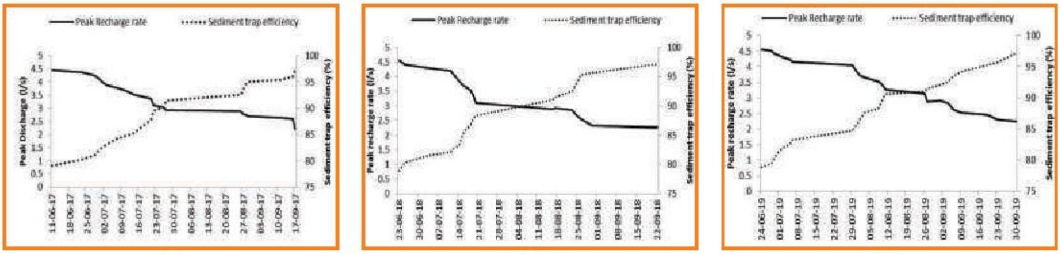
11.0 Hydraulic Performance of Downward Flow Runoff Filter

The peak recharge rate and sediment trap efficiency of both the designs of the runoff filters were found to have an inverse relationship between them as shown in Fig.9 and Fig.10. Initially, the peak recharge rate of both the designs of runoff filters was similar in the range of 4.45 to 4.65 l/s, which was obvious due to similar filter materials used, the analogous thickness of different filter layers, and identical cross-section. The peak recharge rate of downward flow runoff filter design observed for the years 2017, 2018, and 2019 decreased by 51% per year *i.e.* from 4.45 l/s to 2.2 l/s as shown in Fig.9 (a; b; c), respectively. The sediment trap efficiency of downward flow runoff filter design observed for the year 2017 to 2019, increased by 18% per year *i.e.* from 79% to 97% as shown in Fig.9 (a; b; c), respectively. The observed decrease in the peak recharge rate of 51% per year and increase in sediment trap efficiency of 18% per year was due to deposition of sediment carried along with runoff passing through the runoff filter layers (Table 7). The observation shows that most of the sediment gets entrapped in the top 10 cm of the sand layer of the downward flow runoff filter, which reduces the hydraulic permeability of the sand layer exponentially from 7.0×10^{-4} m/s to 3.5×10^{-4} m/s per year. The removal of the top 5 cm of sand layer of the downward flow runoff filter design could recuperate 70-80% of the hydraulic permeability of the sand layer. The sediment trap before the runoff filter was able to trap 42-45% of the sediment in the runoff per year, which is required to be removed at least twice a year. However, the sediment deposited on the top surface of the sand layer of the downward flow runoff filters is required to be removed more frequently at least five to six times per year, depending on the sediment concentration in runoff coming from the crop field for the adequate performance of downward flow runoff filter. The results obtained from laboratory scale model studies for evaluation of these runoff filter designs are in agreement with the above finding.

12.0 Hydraulic Performance of Upward Flow Runoff Filter

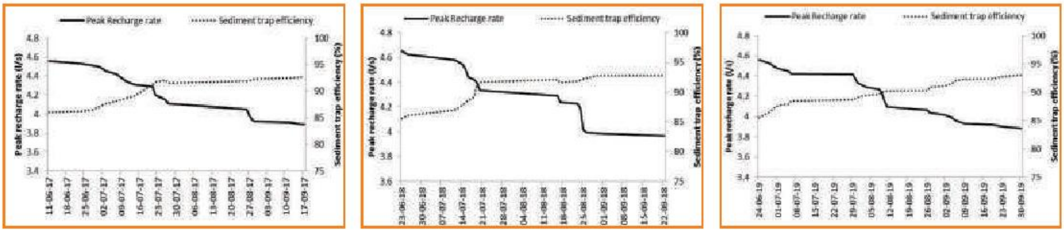
The peak recharge rate of upward flow runoff filter design observed for the years 2017, 2018, and 2019 decreased by 15% *i.e.* 4.56 to 3.89 l/s per year as shown in Fig. 10 (a; b; c), respectively. The sediment trap efficiency of the upward flow runoff filter observed for the years 2017, 2018, and 2019 increased by 6% per year *i.e.* from 86% to 92% as shown in Fig. 10 (a; b; c), respectively. The observed decrease in the peak recharge rate of 15% per year and increase in sediment trap efficiency of 6% per year was due to deposition of sediment carried along with runoff passing through the runoff filter layers. The observation shows that most of the sediments get deposited in the bottom space below the runoff filter layers of upward flow runoff filter designs. The sedimentation was accelerated in upward flow runoff filter design due to a reduction in the velocity of runoff flow through the filter layers. Therefore, in the upward flow runoff filter, most of the sediments in runoff get deposited in the sediment trap and open space at the bottom of the runoff filter layers (Table 8). The hydraulic permeability of the sand layer of the upward flow runoff filter was relatively less reduced from 7.0×10^{-4} m/s to 6.5×10^{-4} m/s per year as compared to the downward flow runoff filter. The sediment trap before the upward flow runoff filter was to reduce 82-85% of the sediments in the runoff per year. The sediment deposited in the sediment trap is required to be removed four to five times per year.

The upward flow and downward flow runoff filter design performed almost similarly in terms of peak recharge rate and sediment trap efficiency. Although, the frequency of sediment removal from the sediment trap of upward flow runoff filter design is more recurrent as compared to the upward flow design. However, removal of deposited sediment from sediment trap is a much easier job as compared to removal of sediments deposited from the top 10 cm of the sand layer of the runoff filter. Therefore, the upward flow runoff filter design requires more frequent maintenance as compared to the downward flow design. The functional working life of the upward flow runoff filter is 4-5 years, whereas the working life of the downward flow runoff filter is 1-2 years. The upward flow runoff filter was found better than the downward flow groundwater recharge filter based on the hydraulic evaluation parameters of peak recharge rate, sediment trap efficiency, frequency of service/dredging/maintenance, and useful working life.



(a) (b) (c)

Fig. 9: (a, b, c) Peak recharge rate and sediment trap efficiency of downward flow runoff filter during 2017, 2018 and 2019



(d) (e) (f)

Fig. 10: (d, e, f) Peak recharge rate and sediment trap efficiency of upward flow runoff filter during 2017, 2018 and 2019

Table1: Hydraulic performance evaluation of downward flow runoff filter during 2017

R_a (mm)	R_u (mm)	PRR (l/s)	PRD (%)	SCI (g/l)	SCO (g/l)	STE (%)	SD (Mg)
20.00	1.04	4.45	100	3.23	0.68	79.09	0.01
34.60	3.03	4.38	98.43	2.54	0.50	80.32	0.02
12.00	5.48	4.26	95.73	1.96	0.37	81.06	0.03
19.00	5.62	4.12	92.58	2.12	0.38	82.09	0.04
12.00	1.36	4.02	90.34	1.94	0.34	82.59	0.01
14.80	2.25	3.89	87.42	1.88	0.32	83.16	0.01
14.80	2.12	3.78	84.94	1.80	0.28	84.23	0.01
17.60	5.15	3.66	82.25	1.83	0.28	84.79	0.03
21.00	5.94	3.52	79.10	1.98	0.29	85.26	0.04
70.00	18.26	3.36	75.51	3.89	0.47	87.89	0.25
65.20	35.15	3.12	70.11	3.65	0.38	89.57	0.46
18.20	5.72	3.04	68.31	2.18	0.21	90.26	0.05
24.80	11.43	2.94	66.07	2.56	0.22	91.52	0.11
20.00	6.22	2.89	64.94	1.89	0.14	92.60	0.04
36.40	12.96	2.78	62.47	2.78	0.18	93.44	0.13
18.00	9.39	2.75	61.80	1.99	0.11	94.56	0.07
25.60	10.45	2.70	60.67	2.20	0.11	95.08	0.09
22.80	1.31	2.64	59.33	2.10	0.10	95.45	0.01
10.80	2.56	2.60	58.43	1.40	0.06	96.07	0.01
21.40	2.12	2.20	49.44	2.30	0.06	97.45	0.02

R_a is Rainfall in mm, R_u is Runoff in mm, PRR is peak rate of recharge in l/s, PRD is peak rate of recharge decrease in %, SCI is sediment concentration at inlet of the runoff filter in g/l, SCO is sediment concentration at the outlet of the runoff filter in g/l, STE is sediment trap efficiency of the runoff filter in %, SD is sediment deposited in the runoff filter in Mg

Table 2: Hydraulic performance evaluation of downward flow runoff filter during 2018

R_a (mm)	R_u (mm)	PRR (l/s)	PRD (%)	SCI (g/l)	SCO (g/l)	STE (%)	SD (Mg)
51.60	1.24	4.56	100	3.12	0.66	78.89	0.01
65.20	6.94	4.42	96.93	2.45	0.48	80.31	0.05
43.60	12.46	4.29	94.08	1.94	0.36	81.56	0.08
74.80	15.7	4.19	91.89	2.98	0.53	82.08	0.15
10.40	2.98	4.09	89.69	1.99	0.35	82.64	0.02
50.00	14.34	3.86	84.65	1.84	0.31	83.22	0.09
14.20	2.44	3.74	82.02	1.90	0.29	84.73	0.02
94.40	39.96	3.67	80.48	3.59	0.51	85.76	0.49
10.00	1.79	3.54	77.63	1.97	0.27	86.54	0.01
13.40	3.55	3.36	73.68	2.56	0.32	87.69	0.03
35.20	6.72	3.1	67.98	3.32	0.39	88.26	0.08
94.20	18.35	2.89	63.38	3.45	0.31	91.04	0.23
35.20	7.6	2.92	64.04	2.46	0.21	91.44	0.07
61.00	11.70	2.84	62.28	3.42	0.25	92.55	0.15
7.20	0.68	2.72	59.65	2.78	0.18	93.42	0.01
29.40	3.27	2.64	57.89	1.99	0.12	94.21	0.02
6.00	1.2	2.55	55.92	2.23	0.11	95.24	0.01
13.00	3.46	2.31	50.66	2.12	0.09	95.66	0.03
41.80	2.30	2.26	49.56	2.43	0.07	97.16	0.02

Table 3: Hydraulic performance evaluation of downward flow runoff filter during 2019

R_a (mm)	R_u (mm)	PRR (l/s)	PRD (%)	SCI (g/l)	SCO (g/l)	STE (%)	SD (Mg)
58.20	0.56	4.56	100	2.12	0.45	78.89	0.00
60.20	33.08	4.5	98.68	3.54	0.73	79.51	0.37
70.40	36.71	4.41	96.71	3.69	0.73	80.31	0.44
55.00	20.12	4.34	95.18	2.98	0.55	81.56	0.20
11.20	3.16	4.28	93.86	1.99	0.36	82.08	0.02
7.40	0.52	4.22	92.54	1.84	0.32	82.64	0.00
63.40	32.48	4.16	91.23	3.25	0.55	83.22	0.35
16.80	4.37	4.05	88.82	1.24	0.19	84.73	0.02
20.60	14.13	3.83	83.99	1.97	0.28	85.76	0.10
49.00	13.16	3.72	81.58	2.56	0.34	86.54	0.12

63.00	15.19	3.64	79.82	3.32	0.41	87.69	0.18
6.80	10.81	3.52	77.19	1.46	0.17	88.26	0.06
56.80	22.16	3.47	76.10	2.46	0.27	89.06	0.19
116.40	19.75	3.37	73.90	3.89	0.38	90.12	0.28
14.40	4.5	3.26	71.49	1.18	0.11	90.57	0.02
24.60	3.45	3.13	68.64	1.02	0.09	91.04	0.01
36.00	14.86	2.87	62.94	2.23	0.19	91.44	0.12
40.00	8.32	2.91	63.82	1.12	0.09	92.08	0.03
43.60	17.66	2.83	62.06	1.43	0.11	92.55	0.09
96.40	55.1	2.71	59.43	3.68	0.25	93.12	0.76
69.40	4.52	2.63	57.68	2.26	0.15	93.42	0.04
13.40	2.01	2.53	55.48	1.02	0.06	94.21	0.01
14.40	5.68	2.45	53.73	1.20	0.06	95.24	0.03
32.60	11.84	2.3	50.44	2.10	0.09	95.66	0.10
8.40	1.52	2.24	49.12	1.09	0.03	97.16	0.01

Table 4: Hydraulic performance evaluation of upward flow runoff filter during 2017

R_a (mm)	R_u (mm)	PRR (l/s)	PRD (%)	SCI (g/l)	SCO (g/l)	STE (%)	SD (Mg)
20.00	1.56	4.56	100	1.26	0.18	86.06	0.01
34.60	4.23	4.53	99.34	1.34	0.18	86.23	0.02
12.00	5.23	4.51	98.90	1.12	0.15	86.46	0.02
19.00	5.59	4.5	98.68	1.16	0.15	86.98	0.02
12.00	1.26	4.49	98.46	1.06	0.14	87.12	0.00
14.80	2.24	4.45	97.59	1.42	0.18	87.67	0.01
14.80	2.17	4.42	96.93	1.31	0.16	88.11	0.01
17.60	5.16	4.34	95.18	1.83	0.21	88.72	0.03
21.00	5.89	4.31	94.52	1.98	0.22	89.06	0.04
70.00	17.89	4.29	94.08	3.46	0.30	91.24	0.23
65.20	34.16	4.2	92.11	3.32	0.28	91.68	0.42
18.20	5.74	4.15	91.01	2.23	0.18	92.12	0.05
24.80	12.24	4.11	90.13	2.86	0.24	91.52	0.13
20.00	6.16	4.05	88.82	1.29	0.10	91.89	0.03
36.40	11.98	3.98	87.28	2.68	0.21	92.03	0.12

18.00	8.96	3.94	86.40	1.99	0.16	92.12	0.07
25.60	11.51	3.92	85.96	2.42	0.19	92.29	0.10
22.80	1.26	3.91	85.75	2.13	0.16	92.46	0.01
10.80	2.24	3.89	85.31	1.21	0.09	92.67	0.01
21.40	3.26	3.89	85.31	2.07	0.15	92.83	0.03

Table 5: Hydraulic performance evaluation of upward flow runoff filter during 2018

R_a (mm)	R_u (mm)	PRR (l/s)	PRD (%)	SCI (g/l)	SCO (g/l)	STE (%)	SD (Mg)
51.60	1.31	4.65	100	3.12	0.45	85.59	0.01
65.20	5.46	4.62	99.42	2.45	0.34	86.04	0.05
43.60	11.46	4.60	98.89	1.94	0.26	86.56	0.08
74.80	14.67	4.58	98.54	2.98	0.39	86.95	0.15
10.40	2.46	4.57	98.36	1.99	0.26	87.17	0.02
50.00	13.98	4.54	97.69	1.84	0.23	87.77	0.09
14.20	2.34	4.51	96.90	1.9	0.22	88.19	0.02
94.40	37.41	4.44	95.52	3.59	0.41	88.67	0.48
10.00	1.56	4.42	95.09	1.97	0.21	89.09	0.01
13.40	3.42	4.40	94.56	2.56	0.22	91.28	0.03
35.20	6.47	4.33	93.16	3.32	0.28	91.67	0.08
94.20	17.86	4.29	92.23	3.45	0.27	92.15	0.23
35.20	8.43	4.24	91.16	2.46	0.21	91.6	0.08
61.00	10.24	4.23	90.92	3.42	0.28	91.87	0.13
7.20	1.44	4.19	90.00	2.78	0.22	92.04	0.01
29.40	3.16	4.02	86.40	1.99	0.16	92.16	0.02
6.00	1.32	4.00	85.96	2.23	0.17	92.39	0.01
13.00	4.25	3.99	85.75	2.12	0.15	92.79	0.03
41.80	2.34	3.97	85.31	2.43	0.17	92.8	0.02

Table 6: Hydraulic performance evaluation of upward flow runoff filter during 2019

R (mm)	R (mm)	PRR (l/s)	PRD (%)	SCI (g/l)	SCO (g/l)	STE (%)	SD (Mg)
58.20	1.56	4.56	100	2.12	0.31	85.56	0.01
60.20	34.56	4.52	99.23	3.54	0.48	86.53	0.42
70.40	37.58	4.50	98.76	3.69	0.48	87.12	0.48
55.00	21.12	4.48	98.14	2.98	0.37	87.54	0.22
11.20	4.16	4.46	97.89	1.99	0.24	87.78	0.03
7.40	0.89	4.45	97.60	1.84	0.22	87.89	0.01
63.40	34.26	4.42	97.00	3.25	0.38	88.46	0.39
16.80	5.16	4.42	96.89	1.24	0.14	88.68	0.02
20.60	13.98	4.33	95.02	1.97	0.21	89.1	0.10
49.00	14.16	4.32	94.68	2.56	0.27	89.26	0.13
63.00	16.34	4.29	94.10	3.32	0.35	89.43	0.19
6.80	10.88	4.27	93.58	1.46	0.15	89.64	0.06
56.80	21.65	4.23	92.87	2.46	0.25	89.85	0.19
116.40	19.48	4.15	91.06	3.89	0.38	90.21	0.27
14.40	4.65	4.09	89.78	1.18	0.12	90.23	0.02
24.60	3.46	4.06	89.14	1.02	0.10	90.32	0.01
36.00	14.87	4.04	88.56	2.23	0.20	90.89	0.12
40.00	8.94	4.02	88.09	1.12	0.10	91.12	0.04
43.60	16.49	3.99	87.56	1.43	0.12	91.45	0.09
96.40	54.22	3.97	87.07	3.68	0.30	91.87	0.73
69.40	4.62	3.96	86.78	2.26	0.18	92.1	0.04
13.40	2.12	3.93	86.16	1.02	0.08	92.31	0.01
14.40	6.42	3.92	86.00	1.2	0.09	92.4	0.03
32.60	12.49	3.90	85.59	2.1	0.15	92.77	0.10
8.40	1.56	3.88	85.14	1.09	0.08	92.98	0.01

Table 7: Sediment budgeting for downward flow runoff filter design

Measured parameters	Values in (m^3)	Values in (%)
Total volume of recharge water	5164.24	-
Total sediments measured at inlet	1.33	-
Total sediments measured at outlet	0.15	11.00
Sediment storage in runoff filter	1.19	89.00

Sediment removed from sediment trap	0.77	64.96
Sediment removed from top of sand section	0.30	25.62
Sediment deposited in other (gravel and pebble) layers	0.06	5.21
Sediment deposited in the pore spaces of the sand layer	0.05*	4.21*

*Values obtained through back calculation

Table 8: Sediment budgeting for improved upward flow runoff filter design

Measured parameters	Values in (m^3)	Values in (%)
Total volume of recharge water	6894.23	-
Total sediments measured at inlet	1.17	-
Total sediments at measured at outlet	0.12	10.45
Sediment storage in runoff filter	1.04	89.55
Sediment removed from sediment trap	0.95	91.14
Sediment removed from top of sand section	0.01	1.28
Sediment deposited in other (gravel and pebble) layers	0.07	6.51
Sediment deposited in the pore spaces of the sand layer	0.01*	1.08*

13.0 Economics of Runoff Filters

The economic analysis was performed for comparing the benefits of constructing the runoff filter to enhance the performance of open wells/bore wells with the cost of construction and the cost of annual maintenance. The average annual recharge through runoff filters varied from 2380 m^3 to 16580 m^3. The groundwater recharged through runoff filter was primarily extracted for irrigation, which varied from 648 m^3 to 9216 m^3 at different locations in Gujarat. The water application was reflected in crop yields realized on these farms located in Gujarat. The annual returns from groundwater used for irrigation were estimated for the agricultural year 2019-20. The additional area brought under irrigation due to enhanced groundwater recharge and the cropping systems practiced in each open/bore well command were analyzed for returns from water use. Input and output prices realized by the individual farmers were considered as the groundwater value in agriculture varies depending upon crops, input levels, management, and prices realized in the local market. The economics of runoff filters studied are given in Table 9. The construction costs of runoff filters were compounded to the year of study, 2019-20. The average capital cost worked out to be □44888/- and the average annual maintenance cost was □729/-, making the total cost as □45617/-. The average energy charge was estimated as □4397/-.

The average return to groundwater use for the runoff filters was estimated as □5.35/m^3, which varied from □1.46/m^3 in Navadh village to □272.39/m^3, with a variation of □0.73/m^3 in Chilklod to □5.94/m^3 in Antisar. The average return to cost ratio for runoff filter worked out to be 2.24, with a variation of 1.09 to 6.56 is given in Table 9. This implied an investment of one rupee in runoff filter gave a return of □2.24/- and suggests that investment in runoff filter is financially viable. Nevertheless, this depends upon rainfall, efficiency of the runoff filter, and crop production performance and is region and context-specific. The use of recharged groundwater along with the management of inputs partly explained the variation. The water extraction for irrigation commensurate with efficient crop management, particularly the irrigation water management for crop production results in better performance of runoff filters.

Table 9: Economics of runoff filters

Location	Number of filters examined	Unit cost of runoff filter (□)	Average return to groundwater use (□/m^3)	Average cost of groundwater extraction (□/m^3)	Return to cost ratio
Aminpura	3	45448.0	8.28	4.66	1.78
Antisar	2	47882.2	27.55	5.94	4.64
Chikhlod	3	50064.0	4.77	0.73	6.56
Dudhelilat	4	53551.3	1.73	0.66	2.65
Kapadivav	2	48757.2	3.86	0.80	4.80
Navadh	4	48582.2	1.46	0.88	1.67
Nana-rampura	14	45002.0	5.03	3.30	1.52
Vejalpur	4	52524.0	3.88	3.57	1.09
Others (Bamaniyalat, Khodiyarnagar, Ramosadi, Vishwanathpura)	5	53671.0	3.08	1.99	1.55
Average	**41**	**-**	**5.35**	**2.39**	**2.24**

14.0 Recommendations

The direct recharge of defunct wells using runoff filters may be a cost-effective alternative of augmenting groundwater recharge artificially in Semi-Arid and Arid regions of the country. The quality of runoff available from crop fields should be assessed for hazardous contaminants before implementing runoff filters. The hydraulics performance parameters of two design of sand-based runoff filter developed for the rainfed Semi-Arid regions of Gujarat was executed from 2017-19. These two designs, downward flow, and upward flow models were formerly tested as a laboratory-scale model and simulated for different suspended sediment loads (1.5 g/l, 2 g/l, and 2.5 g/l) usually observed in runoff from a cultivated crop field. The optimum dimensions of 6 m^2 of the filter design were estimated for farm size of 0.4 ha and average annual runoff of 125 mm at 80% probability for semi-arid conditions of Gujarat. The optimum thickness of filter layers was, Coarse Sand layer 0.3 m, Gravel 0.2 m, and Pebbles 0.6 m with a total thickness of 1.1 m for the filter. The equivalent hydraulic permeability of the filter layer was found to be 2.56×10^{-3} m/s. The hydraulic head in the runoff filter was fixed at 30 cm, considering the height of the bund usually constructed by the farmers in their field. The peak recharge rate of the downward flow runoff filter varies from 4.45 l/s to 4.56 l/s, which decreased from 2.2 l/s to 2.24 l/s (49.5%) in one year. The sediment trap efficiency varies from 78% to 97%, which increased by (19%) in one year. However, the peak recharge rate 4.5 l/s to 4.6 l/s for upward flow design of runoff filter was reduced by only 15% per year to 3.8 l/s to 3.9 l/s. Similarly, the sediment trap efficiency varies from 85% to 92%, which increased by only 7% per year. The hydraulic performance comparison of the upward flow runoff filter was found better in terms of peak recharge rate, sediment trap efficiency, frequency of maintenance, and effective life as compared to the downward flow runoff filter. The exponential decrease in the hydraulic permeability of the sand-based runoff filter was related to the cumulative amount of sediment suspended in the runoff. However, a faster reduction in hydraulic permeability with high sediment concentration can be managed by using an agro-net sheet on the top sand layer for easier maintenance of the downward flow runoff filter. The sharp reduction in hydraulic permeability with the progress of filtration mainly due to clogging of the top 10 cm of the sand layer and significant recovery after removal of top 5 cm of sand layer specifies the prospect to intermittent scraping off as a practical maintenance option for satisfactory recharge rate from the runoff filters. The provisions of sedimentation before the entry of sediment suspended in runoff to the filter in reducing sediment entry to the filter unit which helped maintain better hydraulic permeability indicates the importance of sediment trap. Although, putting agro-net on the top of the filter initially leads to the reduction in hydraulic conductivity but improved the ease of cleaning. An inverse relation between hydraulic permeability and sediment trap efficiency was apparent in both the designs of runoff filters.

With the provision of scrapping off top 5 cm before the beginning of each rainy season or, after the cumulative filtration of about 450 m^3 of runoff, sand-based runoff filter with dimension 6 m^2 was found appropriate for 0.4 ha of an agricultural catchment in the conditions of the Semi-Arid region of Gujarat. However, other factors including the quality of runoff, appropriate geologic conditions, and the benefit-cost must be considered before field adoption. Therefore, considering the above facts the upward flow runoff filter can be a better option for augmenting the groundwater in the Semi-Arid regions of Gujarat.

References

Biswas, A.K., Tortajada, C. and Saklani, U. 2017. India's wells are running dry, fast, The Conversation, https://theconversation.com/indias-wells-are-running-dry-fast78372#:~:text=or% 20nearly%2050%20years%2C%20a,the%20world%2C% 20according%20to%20 NASA (accessed on 03rd February, 2020).

Edward, E.C., Harter, T., Fogg, G.E., Washburn, B. and Hamad, H. 2016. Assessing the effectiveness of drywells as tools for stormwater management and aquifer recharge and their groundwater contamination potential. *J. Hydrol.* 539, pp 539–553.

Gandhi, V.P. and Namboodiri, N.V. 2009. Groundwater Irrigation in India: Gains, Costs and Risks, publication from Indian Institute of Management, Ahmedabad, India, Research and Publication, W.P. No. 2009-03-08, pp 1-38.

Hashimoto, Y., Takashima, H. and Jayamohan, S. 2019. Application of roughing filter to pre-treat 1,000 NTU raw water for slow sand filter. *Water Pract. Technol.* 14 (2), pp 355–364.

Kerby, W.S. 1959. Time of concentration for overland flow. Civ. Eng. 29 (3), 60 (accessed on 29-6-18). https://www.xmswiki.com/wiki/WMS:Kerby_Tc_Equation.

Kumar, G. and Sena, D.R. 2011. Design and development of site specific artificial ground water recharge CSWCRTI annual reports 2010-11. pp 67–68.

Kurothe, R.S., Kumar, G., Sena, D.R. and Tiwari, S.P. 2012. Water quality impacts of artificial recharge–a case study of Central Gujarat. In: Proceedings of the Fifth International Groundwater Conference (IGWC-2012) on the assessment and management of groundwater resources in hard rock systems with special reference to basaltic terrain, Volume III, pp 1048-1064.

Le, Coustumer, L.S. and Barraud, S. 2007. Long-term hydraulic and pollution retention performance of infiltration systems. *Water Sci. Technol.* 55, pp 235-243.

Nassar, A.M. and Hajjaj, K. 2013. Purification of stormwater using sand filter. *Journal of. Water Resource. Prot.* 5 (11), pp1007-1012.

National Water Policy, 2012. by Government of India Ministry of Water Resources. Accessed on 10th October 2018. http://mowr.gov.in/sites/default/files/NWP2012 Eng64 95132651_1.pdf.

Segismundo, E.Q., Kim, L.H., Jeong, S.M. and Lee, B.S. 2017. A laboratory study on the filtration and clogging of the sand-bottom ash mixture for stormwater infiltration filter media. *Water* 9, pp 1-18.

Sharda, V.N., Kurothe, R.S., Sena, D.R., Pande, V.C. and Tiwari, S.P. 2006. Estimation of groundwater recharge from water storage structures in a semi-arid climate of India. *J. Hydrol.* 329, pp 224-243.

Suhag, R. 2016. Overview of ground water in India, pp1-12. https://www.prsindia.org/administrator/uploads/general/1455682937~~Overview%20of%20Ground% 20Water%20in%20India.pdf

Tripathi, B. 2018. Bengaluru, Delhi, Chennai and Hyderabad among 21 Cities to Run Out of Groundwater by 2020. https://www.indiaspend.com/bengaluru-delhi-chennaiand-hyderabad-among-21-cities-to-run-out-of-groundwater-by-2020-2020/.

Winger, R. J. and Ryan, W. F. 1970. Gravel envelopes for pipe drains design. Agricultural Engineering. 51(10), 573p.

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