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Managed Aquifer Recharge at a Farm Level: Evaluating the Performance of Direct Well Recharge Structures

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Abstract: A field study evaluated the performance of direct well recharge structures (DWRS) in order to harvest and filter farm runoff and its discharge into open dug wells to augment groundwater recharge. This was undertaken between 2016 and 2018 using a total of 11 wells in the Dharta watershed, situated in a semi-arid hardrock region of Udaipur district, Rajasthan, India. The depth to water level in each DWRS well was monitored weekly for 1 to 3 years before and after the DWRS was established, and water samples were taken for water quality analysis (pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, fluoride, and *Escherichia coli*) before and during the monsoon period. For each DWRS well, two control wells in close proximity were also monitored and sampled. Five of the DWRS established in 2018 also had flow meters installed in order to measure discharge from the filter to the well. The volume of water recharged through DWRS into individual wells during the 2018 monsoon ranged from 2 to 176 m^3 per well. Although the mean rise in water levels over the monsoon was higher in DWRS wells than in nearby control wells, the difference was not significant. Values of pH, EC, TDS, and F decreased in DWRS and control wells as each monsoon progressed, whereas the turbidity of wells with DWRS increased slightly. There was no significant difference between DWRS and control wells for pH, EC/TDS, turbidity, or fluoride. The presence of *E. coli* in DWRS wells was higher than in control wells, however, *E. coli* exceeded drinking water guidelines in all sampled wells. On the basis of this study, it is recommended that rural runoff should not be admitted to wells that are used for, or close to, wells used for drinking water supplies, even though salinity and fluoride concentrations may be reduced. For this study, none of the 11 DWRS wells produced sufficient additional recharge to potentially increase dry season irrigation supplies to justify expenditure on DWRS. This even applies to the DWRS well adjacent to a small ephemeral stream that had a significantly larger catchment area than those drawing on farmers' fields alone. An important and unexpected finding of this study was that no sampled open dug well met drinking water standards. This has led to a shift in local priorities to implement well-head water quality protection measures for wells used for drinking water supplies. It is recommended that parapet walls be built around the perimeter of such dug wells, as well as having covers be installed.

Keywords: groundwater recharge; water quality; water level monitoring; recharge performance; rainwater harvesting; India

1. Introduction

Water scarcity has become a major problem, especially in most of the arid regions of the world. It ultimately affects food security, natural ecosystems, and plant and human health (Seckler et al., 1999) [1]. Water scarcity arises due to the various anthropogenic factors and one of them is the depletion of groundwater resource. Farmers in semi-arid parts of India use groundwater to save rainfed crops from failure and to increase yields. As it is a relatively cheap and easily accessible water resource for individual farmers, irrespective of their farm size, annual groundwater use often reaches or exceeds the average annual natural recharge. Depth to watertable in hard rock terrain fluctuates considerably during the year, and shallow aquifers become depleted where the use of groundwater has increased; thus, tubewells are drilled to allow pumping from deeper down (in the same or different aquifers), in some areas rendering marginal quality water (Shah, 2009) [2]. The extensive use of groundwater resources by farmers all over the country pumping out water in an unregulated manner creates its own sets of complex management and sustainability issues.

According to a report of CGWB (2017) [3], almost the whole of India shows declining groundwater levels, with the largest declines observed in parts of Rajasthan, Haryana, Punjab, Gujarat, Telangana, and Maharashtra. Water harvesting and recharge enhancement at micro-watershed level have been identified as means to benefit farmers at the village level to address water scarcity (Cavelaars et al., 1994) [4]. However, groundwater levels are declining despite water harvesting measures to conserve water and enhance aquifer recharge, supported on a large scale by watershed development programmes. It is therefore crucial to increase our understanding of the capability and constraints of managed aquifer recharge (MAR) to overcome the threat of groundwater scarcity in the future (Massuel et al., 2014) [5]. Equally important is the understanding of the potential for managing or influencing the new patterns of use (Burke and Moench, 2000) [6], patterns that are often highly dispersed and individualized. To cope with lowering groundwater level, MAR has become an important complementary measure along with demand management to cope with groundwater scarcity (Dillon et al. (2012) [7].

The MARVI project, Managing Aquifer Recharge and Sustaining Groundwater Use through Village-level Intervention (www.marvi.org.in), has demonstrated that it is important to monitor and manage groundwater at the village level, particularly in hard rock areas of India (Maheshwari et al., 2014 [8]; Jadeja et al., 2018 [9]). This approach involves the training of village volunteers and developing a participatory process to assist cooperative management of groundwater. The methods include groundwater data collection at the village level; a methodology to estimate groundwater recharge from simple measurements on check dams (Dashora et al., 2018) [10]); and a smart phone app (MyWell) for collecting and visualising groundwater, rainfall, and check dam data. This approach supports village level decision-making for groundwater use and management. This has been field tested and is considered ready for extended out-scaling across India.

In this study area, village groundwater cooperatives are being formed to help achieve sustainable groundwater supplies. These have informed rabi (winter) crop decision making based on measured groundwater levels. They can also support maintenance of watershed measures for soil and water conservation, including maintenance of streambed recharge structures, as well as encouraging uptake of other options when proven. There is a watershed development program at the state level to increase groundwater recharge through the construction of check dams.

2. Why This Study?

Roof-top rainwater harvesting to recharge dug wells has been widely practiced in India with a varying degree of success (CGWB (2007) [11]; Rainwater Harvesting Association (2020) [12]). However, the use of harvested runoff from farmers' fields to recharge dug wells has been practiced mostly on a trial and error basis (e.g., examples reported in Bali Water Protection Program (2020) [13]), but with relatively rare monitoring. One exception is the work of Pendke et al. (2017) [14], in a study in Maharashtra from 2011 to 2015, who reported 64% removal efficiency of silt in the entry pit containing a preliminary filter rising to 93% removal at the end of the main filter before water is discharged to an open well. This was at a research site with a catchment area of 1.8 ha where runoff was estimated using an uncalibrated model. In 2015, the study was expanded to involve 10 recharge wells and two wells as controls. The size of the catchment areas for these was not reported. In 2015, water table rise was reported to be significantly larger in recharged wells than control wells. Aside from measurement of suspended silt at the pilot site, there was no evaluation of water quality that might impact on the safe use of well water.

The overall aim of this study was to understand the effectiveness of direct well recharge structures (DWRS) to improve groundwater supplies and quality at the local level. The activity reported in this paper arose because some farmers, who were at a considerable distance from streams, perceived that check dams in their catchment were not directly benefiting them as much as farmers whose wells were closer to those check dams. They sought an alternative way of increasing recharge at their wells. They were intending to harvest runoff from fields close to their wells, and divert this into their wells. Researchers from the MARVI team became involved due to well-founded concerns over potential for groundwater contamination. They evaluated wells proposed for direct recharge by farmers to avoid wells used for drinking water supplies, insisted on a filtration step and on monitoring the impacts on levels and quality, and developed a water quality laboratory in the village to enable analyses to be performed. The results of this investigation were to be reported back to farmers before considering any possible ongoing operation. Without these precautionary interventions, this approach could not be considered MAR.

3. Study Area

The study was carried out in the Dharta watershed, which is situated in Bhindar block of Udaipur district of southern Rajasthan, India. This area lies between 24°30′ and 24°37′ N latitude and 73°05′ to 73°15′ E longitude. Four adjoining villages were selected within a radius of 4 km, these being Badgaon, Dharta, Hinta, and Varni, for evaluating the performance of direct well recharge structures (Figure 1). Topography is often undulating with slope up to 2.7%. The ground elevation of the area is 470 m above the mean sea level. The average annual rainfall of the area is about 665 mm (Dashora et al. 2018) [10] and the temperature ranges from 19 to 48 °C in summer and 3 to 29 °C during winter.

The occurrence of groundwater in the watershed is mainly controlled by the topographic and structural features present in the Proterozoic gneisses and schists underlying the area. Groundwater in these rocks occurs in the zone of weathering and in fractures, joints, and foliation plains. When schists are inter-mixed with gneisses, they form a better aquifer (CGWB, 2013) [15]. The depth of dug wells ranges from 14 to 38 m. The major crops grown in the area are maize, wheat, mustard, cluster bean (guar), chickpea, and barley. About 25% of the total land area in the watershed is irrigated by dug wells and tube wells.

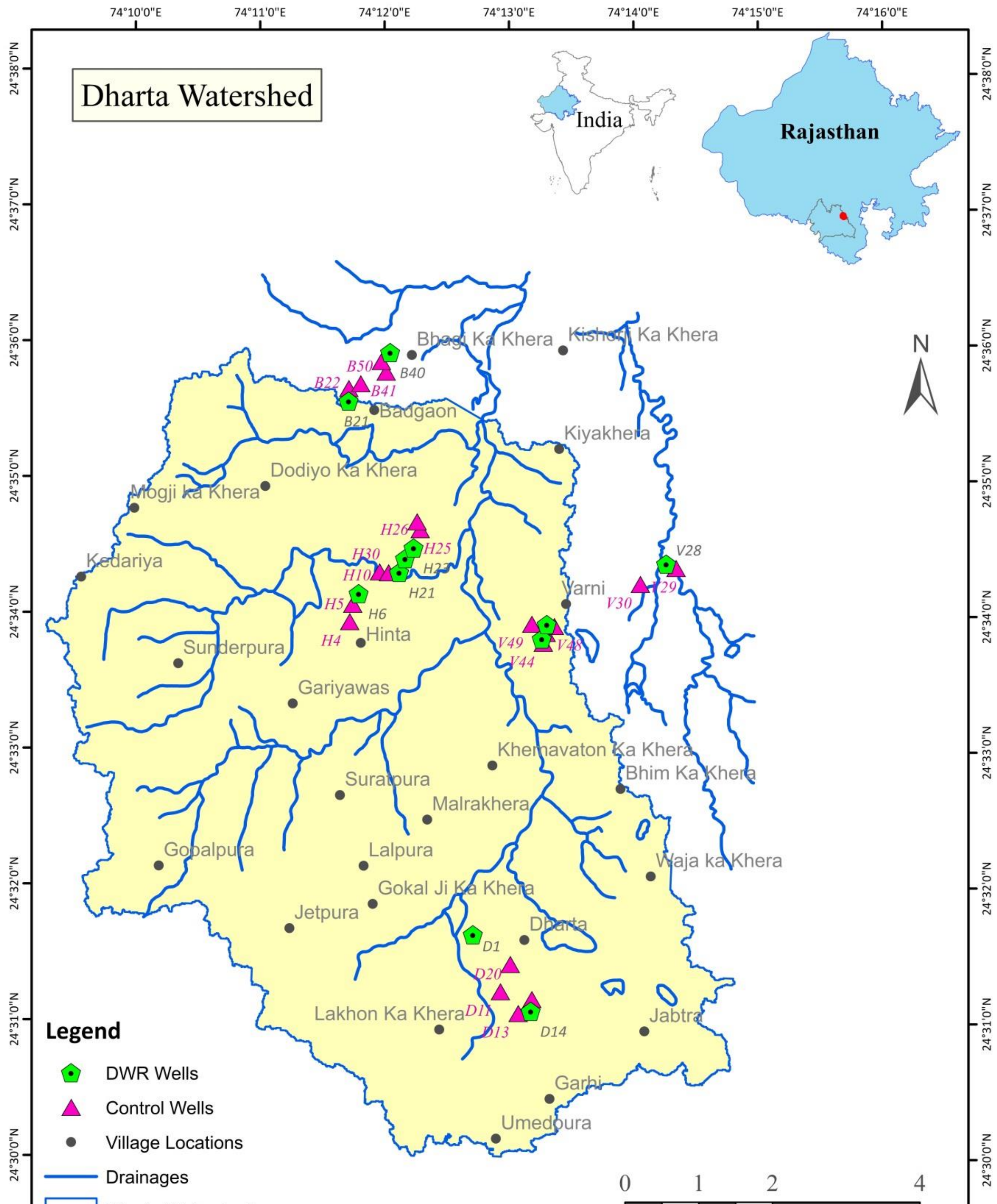


Figure 1. Location map of direct well recharge structures sites in the Dharta watershed and adjacent control wells.

4. Methodology

The study was carried out during 2016–2018. The steps followed in this study were (i) selecting the dug wells for implementing DWRS and nearby control wells, (ii) identifying suitable locations for pits, (iii) building pits and filters to reduce sediment discharge into wells, (iv) installing flow meters, (v) calculating the cost of construction, (vi) monitoring rainfall, (vii) monitoring groundwater levels, and (viii) water quality sampling and analysis.

4.1. Selection of the Dug Wells

With a view to evaluating the performance of direct well recharge at a farm level, a number of dug wells were selected and marked with the code numbers for identification. In the year of 2016, a total of 18 wells were selected, out of which 6 wells were selected for direct well recharge and 12 control wells were selected, with 2 separate wells in close proximity to each DWRS well. In 2018, an additional 15 wells were selected, and out of these, 5 wells were used as DWRS wells and 10 as control wells, again with 2 controls close to each DWRS well. Only the DWRS wells constructed in 2018 were fitted with flow meters to estimate the annual recharge volume. Hence, in 2018, there were a total of 11 DWRS wells and 22 wells as controls (Table 1). All the control wells were in close proximity to their recharge wells. Further, the wells in Table 1 are identified by whether they have parapet walls, overhanging trees and rotten plant debris, or whether they are fitted with flow meters for measuring runoff discharge into the wells. All wells are used for irrigation supplies.

Table 1. Total well depths of direct well recharge structures (DWRS) and control wells.

	DWRS Well	Total Well Depth, m	Control Well (1)	Total Well Depth, m	Control Well (2)	Total Well Depth, m
2016	H6 [ab]	19.60	H4 [a]	24.50	H5	17.65
	H21	28.90	H30 [b]	29.20	H10 [a]	25.40
	B21	20.50	B22 [a]	23.20	B44	20.60
	B40	18.45	B41	23.20	B50	27.90
	V43	30.45	V44 [a]	35.80	V45 [a]	33.10
	V47 [ab]	27.10	V48 [a]	28.45	V49 [ab]	30.10
2018	H22 [a] *	21.20	H30	29.20	H10 [a]	25.40
	H23 *	18.30	H25	24.30	H26	21.80
	D1 *	32.10	D11 [a]	18.95	D20	19.60
	D14 *	31.20	D13 [a]	22.80	D15	31.00
	V28 [ab] *	19.20	V29 [a]	19.10	V30 [ab]	22.70
	Average depth (m)	24.3	-	25.3	-	25.0

* = DWRS wells established in 2018 were fitted with flow meters. [a] = well with parapet wall; [b] = wells without overhanging trees and rotten plant debris. All wells were infested with birds.

4.2. Identification of Suitable Locations for Pits

It was considered important that the recharge pit (details described below) was located close to the recharge well to reduce the cost, and it was also located such that the runoff could easily flow towards the pit. For this, the important consideration was the general slope of the runoff contributing area. An earthen channel was constructed to guide runoff towards the pit. The catchment area was a secondary consideration, and subsequently this was identified as constraining the measured benefits. If the pit filled during a rainfall event, excess flow diverted along natural drainage lines and did not enter the well.

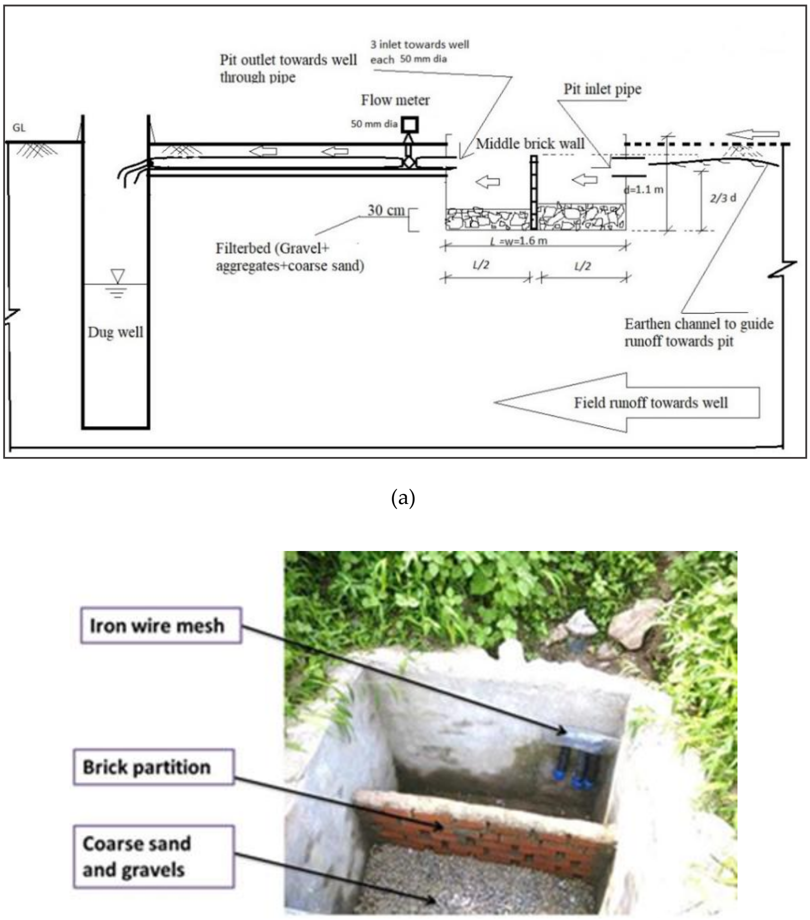
4.3. Pit and Filter Constructions and Pipe Installations

The pits were dug near the recharge wells with the help of earth moving machinery. The size of the pits varied slightly due to construction method. The median length, width, and depth of pits were 1.40, 1.55, and 1.15 m, respectively (Table 2). Once the pit was dug to the required dimensions, the masonry work was done on the four sides of the pit walls to maintain the stability of the pits. The bottoms of the pits were cemented, incorporating stones from a local quarry. The pit was divided into two sections by a brick wall constructed in the middle with a height of about two-thirds of the pit depth. This division was done to allow extra deposition time of sediments in the pit, as reported useful by Pendke et al. (2017) [14]. Runoff from pits was discharged from the pit into the recharge well through one or more 50 mm diameter high-density polyethylene (HDPE) pipes, which were laid in a trench to allow gravitational flow and perforated the well perimeter through an aperture just large enough to contain the pipe(s). The pipe inlets were installed about 0.2–0.3 m above the bottom of the pit to minimize clogging of the inlets (Figure 2). In some wells, two or even three pipes of 50 mm diameter were used in order to increase the proportion of runoff that entered the pit and well. After pipe installation, the trench was backfilled and compacted.

Table 2. Design details of DWRS pits.

DWRS Code	Length, m	Width, m	Depth, m	Volume (m^3)	Catchment Area (m^2)	Vol as mm over Catchment Area
H6	3.35	1.90	1.00	6.40	1131	5.6
H21	0.90	1.35	1.15	1.40	585	2.4
B21	1.15	1.20	0.70	1.00	2343	0.4
B40	2.30	2.30	1.10	5.80	1155	5.0
V43	1.90	1.90	1.20	4.30	304	14.3
V47	1.90	1.80	0.85	2.90	263	11.1
H22 *	1.20	1.40	1.10	1.80	3200	0.6
H23 *	1.40	1.55	1.20	2.60	662	3.9
D1 *	1.00	1.37	1.22	1.70	2860	0.6
D14 *	1.34	1.13	1.22	1.80	11,954	0.2
V28 *	1.40	2.40	1.30	4.40	2,902,300	0.0
Median	1.40	1.55	1.15	2.60	1155	2.4

* DWRS well established in 2018.



(b)

Figure 2. View of DWRS installed in the study: (**a**) a cross-sectional view of DWRS (not to scale); and (**b**) photograph of a sample structure constructed in the study area.

4.4. Reducing Sediment Discharge into Wells

The runoff carries suspended sediment particles throughout the rainy season, although the concentration was expected to be highest at the beginning of the monsoon season, when the ground was parched and there was no vegetation cover. It was considered important to prevent the discharge of sediments into the DWRS well in order to reduce the likelihood of turbid water clogging the fractures that allowed natural ingress of groundwater. A simple and cheap roughing filter was devised in which coarse sand and stone aggregates were placed in the pit on both sides of the dividing wall and covered with net cloth to help make suspended sediments settle in the pit and allow easy removal of detritus. Table 2 reports gross volume of pits, not accounting for filter material; hence, the holding capacity for water was quite small (<6.4 m^3) in relation to typical monsoon rainfall events, which could exceed 60 mm in a day.

4.5. Installation of Flow Meters

In the five DWRSs constructed in 2018, a flow meter was installed between the pit and recharge well to monitor the cumulative volume of water discharged into those wells. Flow meters with 50 mm diameter were used to measure the total volume of the runoff water discharged in a single pipe. If there were more than one pipe, it was assumed that other pipes discharged the same volume as the metered pipe. For additional protection of water meters from clogging due to plant debris in runoff water, iron wire meshes were placed at the inlet of pipes. A schematic diagram of field settings of components of the recharge structure are shown in Figure 2a, and a photo of a typical structure (one of 11) is shown in Figure 2b, whereas Figure 3 shows the discharge of runoff into a well after it has passed through the filter. The dial pad reading of the flow meter was recorded photographically at the time of installation, and subsequently after every runoff event.

Figure 3. Runoff discharge into well after it was collected in the pit and had passed through the filter.

4.6. Managed Aquifer Recharge Operations

For the DWRSs constructed in 2016, managed aquifer recharge (MAR) commenced in July 2016 and continued through the monsoons of 2017 and 2018, generally over the months of July to October. For DWRSs constructed in 2018, MAR commenced in July 2018. The systems were shut down at the end of the 2018 monsoon. DWRS and control well water levels were measured weekly from January

2013 to December 2018 for the wells of Hinta, Dharta, and Badgaon village, whereas for the Varni village, monitoring was done from December 2013 to December 2018.

4.7. Calculating the Cost of Construction

The cost of construction of the recharge pits varied on the basis of the location and material used. Locally available construction material was used, and well owners were engaged throughout the construction process. All the cost components starting from digging the pit to installing water-meter and outlet pipes were recorded. The cost of construction and installation depended on access to the site, distance between pit and recharge well, and construction of runoff collection field channel (wherever necessary). Only existing wells were used, and thus these are regarded as a sunk cost. The site specific average estimate of cost for installing a DWRS is given in Table 3, in Indian rupees at 2018 costs.

Table 3. Installation cost of a DWRS structure at field site (for conversion USD 1 = INR 70 in 2018).

Items	Quantity	Cost, INR	Cost, USD
Hiring cost for earth moving equipment	1 h	800	11
Stones	1 trolley load	1300	19
Coarse sand	$\frac{1}{4}$ trolley load	600	9
Cement bag	2	600	9
Bricks for partition	50	250	4
Stone aggregates	$\frac{1}{4}$ trolley load	300	4
Pipes (m)	3	600	9
Builder and labour	1 + 1	1600	23
Flow meter *	1	4500	64
Total cost without flow meter		6050	86
Total cost with flow meter		10,550	151

* Installed for flow measurement.

4.8. Rainfall Monitoring

Rainfall monitoring was done on a daily basis by farmer volunteers, known as BJs (Bhujul Jaankaars or "groundwater informed"). Rain gauges were installed in all four villages, and annual rainfalls were recorded (Figure 4) by BJs. To evaluate the effect of the runoff on the water level fluctuation of the wells, the rainfall data obtained were used to correlate with the water table level and the influence of the recharge pit for specific rainfall events.

4.9. Groundwater Level Monitoring

Groundwater level monitoring was done at a weekly interval and commenced a few weeks before the monsoon, continuing until after the end of the monsoon season when levels had peaked and were in decline. An ordinary measuring tape with a float at its end was used for monitoring the depth to water level in each DWRS and control well, below a datum that was marked on the well head with the well identification number. Readings were taken by the farmer BJs who had been trained to undertake such measurements and had considerable experience. The water level data obtained during weekly monitoring were used to plot well hydrographs.

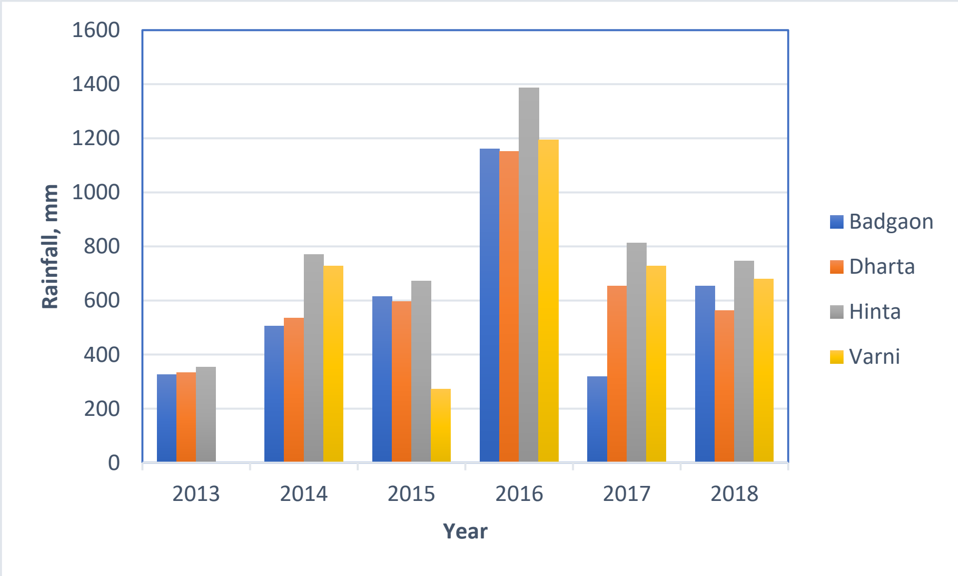


Figure 4. Annual rainfall in study villages during the study period, 2013–2018.

4.10. *Water Quality Monitoring*

4.10.1. Sampling

Water samples were taken on five occasions for analysis of pH, EC/TDS, and turbidity—July 2015, July 2017, June 2018, August 2018, and October 2018. Samples were analysed for fluoride on three of these occasions—July 2017, June 2018, and August 2018. *Escherichia coli* analysis was conducted on the water samples collected in August, September, and October 2018.

4.10.2. Physical and Chemical Analyses

The water samples were collected in order to analyse pH, EC, TDS, turbidity, and fluoride. They were analysed in the field for these physico-chemical parameters using an Aquaread instrument (https://www.aquaread.com/portofolio/ap-5000/) to test pH, EC, TDS, and turbidity. A HACH DR/890 portable colorimeter (https://www.hach.com/dr-890-portable-colorimeter/product?id=7640439041) was used to measure fluoride (F) concentration. *E. coli* samples were collected and taken to a laboratory in the Hinta village for analysis within 8–24 h, and samples were stored in a refrigerator for the time period between sampling and laboratory analysis. On each day of sampling before testing of water samples, the instruments were calibrated using distilled water and stock solutions. On one occasion, a split set of 10 samples was provided to an independent university laboratory for analysis of TDS (by EC) and fluoride. The coefficient of determination (R^2) for TDS was 0.82, and in terms of fluoride, R^2 was 0.98 for samples within the prescribed range of <2–2.5 mg/L for the colorimeter. To establish the reliability of the measurements, the testing of duplicate water samples was carried out. The results indicated average differences for 10 samples for pH, EC, TDS, and F and for 9 samples for turbidity of between 2.5% and 5% of the range in observed values. Hence, these field data are considered reliable for the purposes of the investigation.

4.10.3. Bacteriological Analysis

The MacConkey Agar (MAC) method was used to grow *Escherichia coli* bacteria. For the bacteriological analysis, standard lab procedure was used—the MAC flasks, spreader, and Petri dishes were sterilized in an autoclave at 120 °C at 15 psi for 15 min, after which spreading of field samples was done under laminar flow conditions. The MAC was poured into sterilized Petri dishes on which *E. coli* was cultured. This agar provides a solid medium on which selected bacteria are able to decompose agar. MAC is a selective and differential medium designed to selectively isolate Gram-negative bacteria such as *E. coli* and enteric bacilli on their ability to ferment lactose. Groundwater samples of DWRS wells and control wells were tested for microorganisms that would ferment lactose to produce end products that react with the pH indicator neutral red and would produce a pink colour colony. Results were reported as *E. coli* log colony-forming units (CFU)/mL.

5. Results and Discussion

The results of the evaluation of DWRS at a farm level are presented and discussed below.

5.1. Recharge in DWRS Wells

The metered volume of water recharging wells could only be determined at three DWRS wells in 2018 due to meter failures at two sites. Failures were thought to be caused by detritus clogging the impellors on mechanical flow meters in spite of the precautions taken. For the two sites representative of the catchment areas for 10 of the 11 DWRS wells, the average recharged proportion of monsoon rainfall on the catchment areas was 1.17%. This is considerably lower than the estimated 17% runoff generated from rainfall in 10 Maharashtra DWRS catchments (Pendke et al. 2017) [14]. It was observed that pits filled in heavy storms and subsequent runoff bypassed DWRS. Applying the average proportion of catchment rainfall recharged from these two wells to all other DWRS wells in all years since they were established gives the volumetric recharge estimates shown in Table 4.

Table 4. Observed and estimated recharge through DWRS pits.

Well ID	Year of Pit Establishment	Recharge Volume Metered, m^3	Recharge as mm over Catchment	As % of Rainfall on Catchment	Estimated Recharge, m^3		
					2016	2017	2018
H6	2016			*	13	7	10
H21	2016			*	7	4	5
B21	2016			*	22	6	18
B40	2016			*	11	3	9
V43	2016			*	3	2	2
V47	2016			*	3	2	2
H22	2018	27	8.44	1.13%			27
H23	2018			*			4
D1	2018			*			13
D14	2018	81	6.78	1.20%			81
V28	2018	176	0.06	0.01%			176
Mean				1.17%*	14	6	32
		Total (pits established in 2016)			**59**	**24**	**46**
		Total (pits established in 2018)			**0**	**0**	**309**
		Total			**59**	**24**	**355**

* The mean value for H22 and D14 was applied to all unmetered sites and sites where meters failed to register. V28 represents a DWRS well besides a stream with a catchment area three orders of magnitude larger than the median of the DWRS sites, and hence was excluded from estimation of recharge at other wells.

The volumes of recharge are very low, in part due to the small catchment area of farm fields, in part by the low proportion of runoff diverted into wells due to the very small volumes of pits (Table 2) with respect to typical monsoon rainfall events, and possibly in part due to under-estimation of recharge by under-performing flow meters.

5.2. Head Rise Comparison between DWRS Wells and Control Wells

Six DWRS wells were constructed in 2016 and another five in the year 2018 (Table 1), and in this catchment that had been intensively monitored since 2013 in the MARVI project (Maheshwari et al. 2014) [8], we calculated the head rise in each well by subtracting the depth to water level at the end of the monsoon from that at the beginning of the monsoon. The ratio of head rise of each DWRS well to the mean of its adjacent control wells was calculated for each year (2013 to 2018). Subsequently, the change in these ratios was analysed to compare head rises before and after construction of DWRS for both construction years (2016 and 2018). Table 5 shows the mean and standard deviation of the head rise ratios.

Table 5. Statistical analysis of ratio of mean head rise of each DWRS and nearby control wells.

DWR	2012	2013	2014	2015	2016	2017	2018	Mean before Construction	Mean after Construction	Mean (after Minus before)
H6 ##	0.72	0.54	0.12	0.88	0.85	1.63	0.72	0.56	1.07	0.51
H21 ##	1.35	0.71	0.70	2.06	0.86	0.86	0.89	1.20	0.87	−0.33
B21 ##	0.88	0.55	0.66	1.72	0.91	1.02	1.24	0.95	1.06	0.11
B40 ##	0.52	0.73	0.63	1.30	0.75	0.78	0.64	0.80	0.72	−0.07
V43 ##			0.79	1.20	0.76	2.39	1.17	1.00	1.44	0.44
V47 ##			0.25	0.24	0.82	1.06	1.20	0.25	1.02	0.78
H22 *	0.65	0.17	0.31	0.36	0.49	0.77	0.91	0.37	0.91	0.54
H23 *	0.37	0.08	0.02	0.48	0.60	0.81	0.76	0.23	0.76	0.53
D1 *	1.81	2.21	4.39	2.95	1.78	1.31	3.49	2.41	3.49	1.08
D14 *		1.33	1.36	1.24	1.17	1.14	2.15	1.31	2.15	0.84
V28 *			0.26	0.51	1.26	0.91	2.12	0.38	2.12	1.74
Summary statistics of head rise ratio by year										
Mean	**0.90**	**0.79**	**0.86**	**1.18**	**0.93**	**1.15**	**1.39**	**0.86**	**1.42**	**0.56**
SD	**0.51**	**0.69**	**1.23**	**0.82**	**0.36**	**0.49**	**0.87**	**0.64**	**0.85**	**0.57**
CoV	**0.57**	**0.87**	**1.42**	**0.70**	**0.38**	**0.42**	**0.62**	**0.74**	**0.60**	**1.01**
Values below are for DWR wells commencing in 2016 only ##										
Mean	0.87	0.63	0.53	1.23	0.83	1.29	0.98	0.79	1.03	0.24
SD	0.35	0.10	0.27	0.64	0.06	0.62	0.26	0.34	0.24	0.41
CoV	0.41	0.16	0.52	0.52	0.08	0.48	0.27	0.43	0.23	1.73
Values below are for DWR wells commencing in 2018 only *										
Mean	0.94	0.95	1.27	1.11	1.06	0.99	1.89	0.94	1.89	0.94
SD	0.77	1.02	1.82	1.09	0.53	0.23	1.11	0.92	1.11	0.50
CoV	0.81	1.07	1.44	0.98	0.50	0.23	0.59	0.98	0.59	0.53

DWRS constructed in 2016; * DWRS constructed in 2018; Bold is summary for all DWRS wells.

The statistical analysis of ratio of mean head rise of DWRS and control wells indicated that the effect of DWRS to raise water level in DWRS was not statistically significant at $p < 0.05$. This is not surprising due to the fact that the natural recharge in the area is considerably larger than the generally small additional volumes of water recharged through DWRS. This, combined with the local factors such as geology, topography, and rainfall intensity variations, can mask the DWRS contribution to the aquifer. The maximum increase in head rise ratio was observed at DWRS V28 (which had the highest recharge volume, more than three times the next highest measured or estimated value (at D14)) (Table 4).

Pendke et al. (2017) [14] studied direct well recharge at 10 sites in the Maharashtra state of India and observed that the difference between the post-monsoon (September) and pre-monsoon (June) water level depths was greater when compared with those of two controls. However, the catchment areas were more than 10 times the median in the Dharta case study, but inflow volumes were not recorded. It is expected that head rise in individual wells is unlikely to be an effective diagnostic of DWRS recharge effectiveness. Variations in transmissivity and specific yield in the aquifer could even suggest the reverse is true where for the same recharge volume the groundwater mound would be higher for aquifers with low transmissivity and low specific yield. Reliable measurements of recharge are the most decisive information on which to assess recharge effectiveness, as found for check dams in the same catchment by Dashora et al. (2018, 2019) [10,16].

5.2.1. Water Quality

The water quality information for the various wells in four villages is summarised in Table 6.

Table 6. Water quality parameter values DWRS and control wells for different villages during the study period.

Parameter	Badgaon		Dharta		Hinta		Varni		All Villages		All Villages
	DWRS Wells	Control Wells	DWRS Wells	Control Wells	DWRS Wells	Control Wells	DWRS Wells	Control Wells	DWRS Wells	Control Wells	DWRS Wells – Control Wells
No. of wells	2	4	2	4	4	6	3	6	11	20	
No. of samples	6	12	6	12	12	18	9	18	33	60	
pH (mean)	7.92	7.85	7.76	8.04	7.8	7.87	8.06	8.07	7.89	7.96	−0.07
pH (standard deviation)	0.32	0.24	0.43	0.18	0.21	0.29	0.42	0.37	0.33	0.28	
TDS (mean), mg/L	1772	2676	1649	2031	3081	2937	2571	2041	2444	2435	9
TDS (standard deviation), mg/L	690	1705	319	415	1604	1504	1591	970	1201	1166	
Turbidity (mean), NTU	36.02	61.71	57.72	82.7	80.99	76.16	37.13	30.98	57	61	−4
Turbidity (standard deviation), NTU	20.15	48.67	51.34	113.42	63.81	57.58	28.83	29.55	44	59	
No. of samples fluoride	4	8	4	8	8	12	6	12	22	40	
Fluoride (mean), mg/L	1.12	0.77	0.74	1.06	0.98	0.94	0.95	1.03	0.95	0.96	0.00
Fluoride (std. deviation), mg/L	0.41	0.38	0.37	0.36	0.49	0.37	1.03	0.21	0.60	0.32	
No. of samples *Escherichia coli*	8	10	7	11	16	20	12	12	43	53	
E. coli (mean), log number CFU/mL	3.26	2.83	3.04	2.55	3.06	3.06	2.81	2.48	3.02	2.78	0.24
E. coli (standard deviation), log number CFU/mL	0.46	0.47	0.69	0.65	0.45	0.38	0.32	0.31	0.45	0.44	

5.2.2. pH

Water samples were collected and tested for pre-monsoon (Jun 2018), during monsoon (July 2015, July 2017, and August 2018), and post-monsoon (October 2018) periods. The mean pH values of most of the DWRS and less of their control wells were found to be between the permissible limits (6.5–8.5) of the Bureau of Indian Standards (BIS; 2004) [17]. Figure 5 shows the percentage of samples that met the (BIS) criteria. Both in July 2015 (before any DWRS recharge) and October 2018 (post-monsoon), all the DWRS wells met the criteria, whereas half of the control wells had a pH greater than 8.5. In 2017, only about 26% of samples of both DWRS and control wells met the criteria due to elevated pH. That is, the introduction of DWRS made little difference to the acceptability of the pH of the water for drinking.

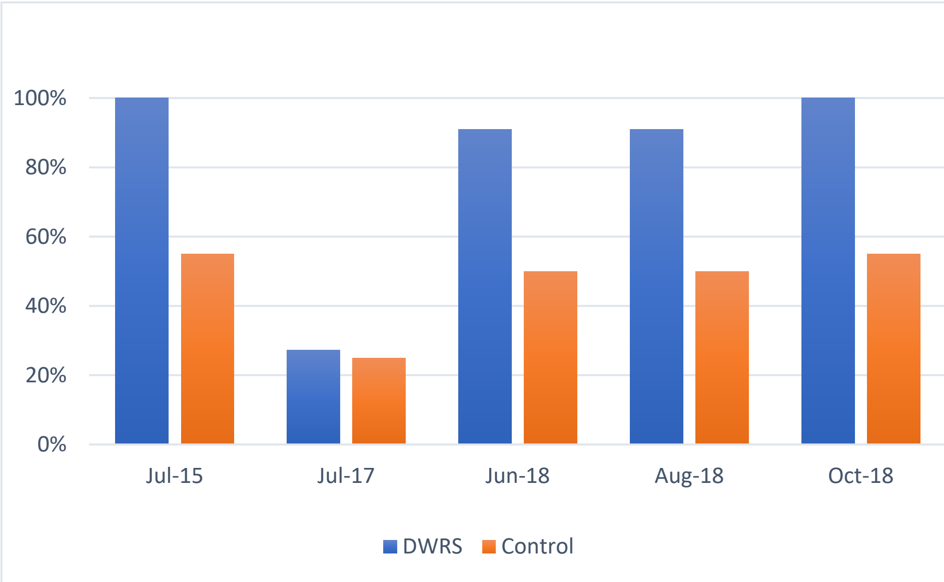


Figure 5. Percentage of samples meeting Bureau of Indian Standards (BIS) guidelines for pH in drinking water with or without an alternative supply (BIS acceptance range pH: 6.5–8.5).

5.2.3. TDS

In July 2015, about 82% samples of DWRS met BIS criteria (TDS (2000 mg/L), compared with 55% for the control wells (Figure 6). Although a higher proportion of DWRS wells than control wells had TDS less than 2000 mg/L, before and during occurrence of DWRS recharge, it is evident that these proportions can increase during the monsoon for both DWRS and control wells due to dilution with fresh natural recharge. However, the volume of DWRS recharge in the DWRS wells is so small that it does not make a marked benefit if wells were to be used for drinking, and it will be seen that other parameters relevant for drinking are adversely impacted by DWRS.

5.2.4. Fluoride

The average values of fluoride of DWRS and control wells ranged from 0.75 to 1.13 mg/L and 0.83 to 0.94 mg/L, respectively. The proportion meeting the BIS criteria (<1.5 mg/L in the absence of an alternative supply) of DWRS was 73% in July 2017, compared with 55% for control wells (Figure 7). Between June 2018 (before monsoon) and August 2018 (mid monsoon), the proportion of DWRS wells with $F < 1.5$ mg/L increased with respect to control wells. This is not surprising because of the generally lower ambient TDS and F of DWRS wells than in control wells, and thus rainfall recharge is expected to have a greater diluting influence in DWRS wells.

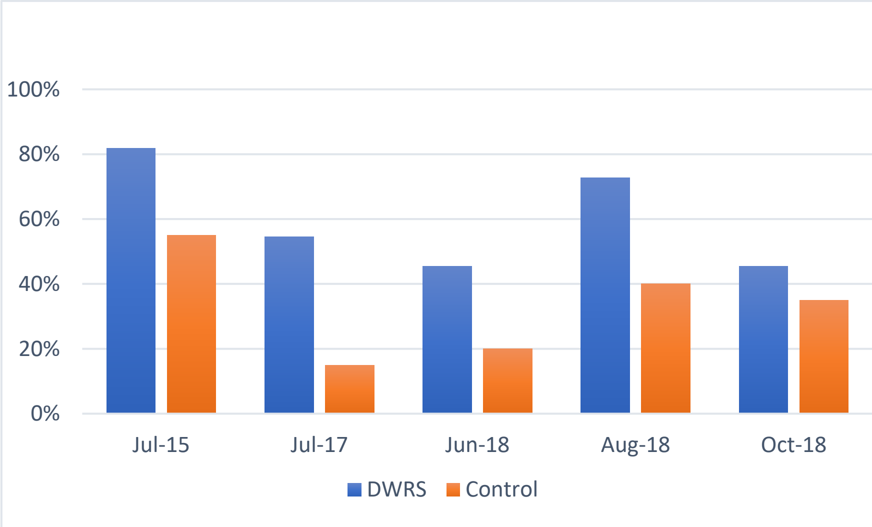


Figure 6. Percentage of samples meeting BIS guideline for TDS in drinking water in the absence of an alternative supply (BIS threshold < 2000 mg/L).

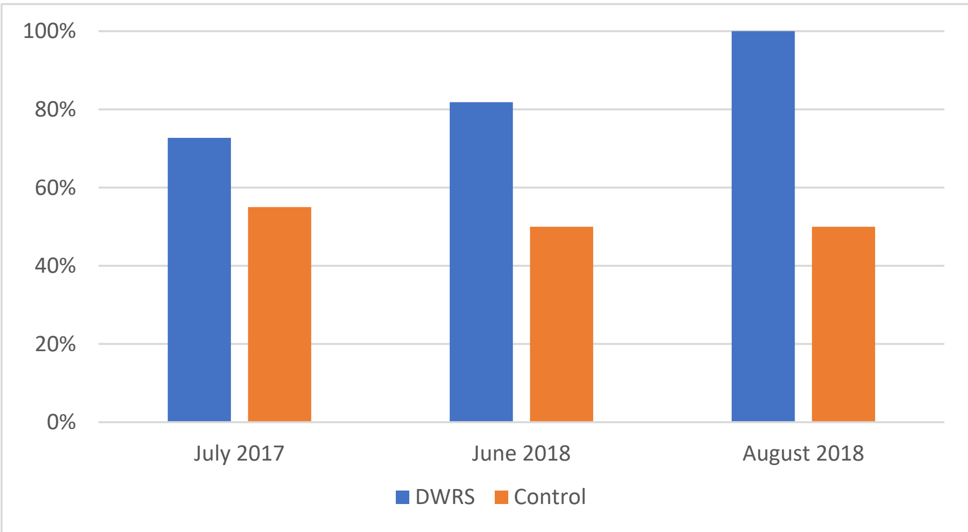


Figure 7. Percentage of groundwater samples that meet BIS guidelines for fluoride in drinking water in the absence of an alternative supply (BIS threshold < 1.5 mg/L).

5.2.5. Turbidity

As indicated in Table 6, the mean values of the turbidity of DWRS and control wells ranged from 30 to 65 and 29 to 66 NTU (Nephelometric Turbidity Units), respectively. As illustrated in Figure 8, from the years 2015 to 2018, none of the samples met the BIS criteria (10 NTU in the absence of an alternative supply) except in June 2018 (DWRS 27% and control 20%) before the monsoon broke, as well as in October 2018 (only control 10%). It was found that wells with parapet wall (45 NTU) had less turbidity when compared to wells without parapet wall (54 NTU). This suggests that a parapet wall alone may be insufficient in providing adequate protection for drinking water wells in this area.

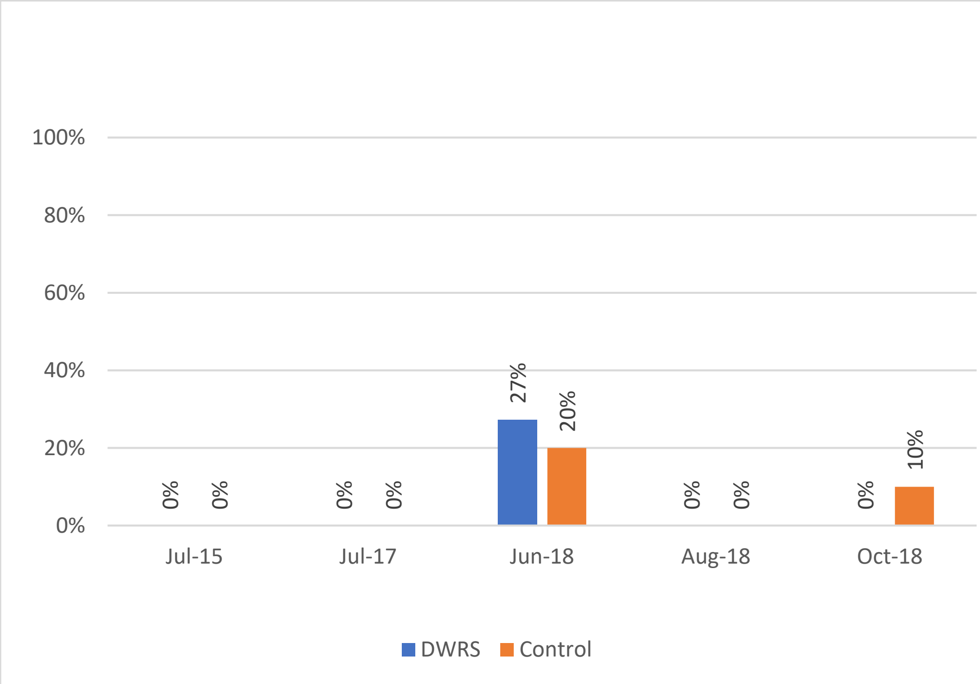


Figure 8. Percentage of samples of samples meeting BIS criteria for turbidity in drinking water in the absence of an alternative supply (<10 NTU).

5.3. *E. coli*

The presence of *E. coli* bacteria in any 100 mL sample of water indicates that the water is contaminated and unfit for drinking (BIS standards). The water samples for both DWRS and control wells were tested and found that not only the wells that were recharged but also control wells showed the presence of *E. coli*. Table 7 shows the mean of DWRS wells was between 0.12 and 0.68 log CFU/mL higher than the mean of control wells; however, in relation to standard deviations, this departure was not significantly different.

Table 7. *E. coli* log number colony-forming units (CFU)/mL of DWRS and control wells.

Date	Number of Wells		Mean Value of *E. coli*, log CFU/mL			Standard Deviation, log CFU/mL	
	DWRS	Control	DWRS	Control	DWRS - Control	DWRS	Control
16-08-2018	10	0	2.77	-		0.39	-
25-08-2018	10	12	3.03	2.35	0.68	0.54	0.70
25-09-2018	11	19	3.15	2.70	0.45	0.57	0.65
06-10-2018	9	16	3.22	3.10	0.12	0.46	0.48
All samples	40	47	3.04	2.75	0.29	0.49	0.61

The data revealed that both DWRS and control wells were found to be infected by E. *coli*. It was also noticed that the control wells that did not have a well-constructed parapet were affected by the bird droppings and rotten plant debris in creating the possibility of the *E. coli*. No wells had covers, and only 15 wells out of a total of 31 wells monitored had a parapet wall. It was found that wells with parapet walls had a lower average number of *E. coli* (2.47 log CFU/mL) than wells without parapet walls (2.85 log CFU/mL) (Table 6). The wells with over hanging trees and bird activities inside wells had *E. coli* 2.92 log CFU/mL, whereas without hanging trees showed *E. coli* 2.09 log CFU/mL. There were no wells with covers to keep out birds and bats from well heads, and thus it was possible these were the source of *E. coli* found in all wells.

The Water Quality Guide for Managed Aquifer Recharge in India (Dillon et al. 2014) [18] allows for a very simple approach to accepting natural water to recharge an aquifer if the recharge mechanism does not bypass the unsaturated zone. If the unsaturated zone is bypassed, as is the case in DWRS, the guide then refers proponents to the Australian Guidelines for MAR (NRMMC, EPHC, NHMRC (2009) [19]. These require a monitoring regime to ensure that the aquifer is not polluted, which could have an adverse impact on human health or the environment. Although the monitoring effort undertaken in this study did not cover all potentially present contaminants, such as agricultural organic chemicals, nutrients, and other types of microorganisms such as viruses and protozoa, the selection of parameters is sufficiently convincing in order to demonstrate the fact that improved treatment is required if any well influenced by the water introduced via DWRS is used for drinking water supplies.

5.3.1. Performance of Filters and Potential for Fracture Clogging

The runoff water was filtered before redirecting it into the recharge well to retain suspended sediments and thereby reduce the blockages of fractures (see Figure 9) and improve the groundwater quality. During the first two to three rainfall events in the study, we observed that the surface water carried with it considerable amounts of suspended fine silt particles and organic plant materials, including rotten leaves and plant debris. The filter bed made up of coarse sand and gravels retained much of the suspended silt. It was also observed that timely manual cleaning of the pit, namely, the removal of the silt and plant debris, was an important activity to reduce any blockage of the discharge pipe inlets. During the monitoring, on some occasions, the water meters were observed as being clogged by plant debris, and thus to overcome this problem, we installed a wire mesh at each flow meter inlet.

Figure 9. Recharge pit with filters. and clogging of the flow meter inlet.

For the long-term success of DWRS structures, removal of any suspended material through filtering is important before runoff water is discharged into wells to avoid potential clogging of aquifer fractures. Clogging has been observed a significant issue in Australia when stormwater runoff and treated municipal waste-water effluent are injected into aquifers to produce water for irrigation (NRMMC, EPHC, NHMRC 2009) [19]. Baveye et al. (1998) [20] reported that the main problem in infiltration systems for enhancing recharge of groundwater is clogging of the infiltrating surface (basin bottoms, walls of trenches and vadose-zone wells, and well-aquifer interface in recharge wells), resulting in reduced infiltration rates. Silt removal is done mechanically with scrapers, front-end loaders, and graders, or manually with shovels and rakes.

5.3.2. Costs and Benefits of DWRS

The costs of establishing a DWRS without and with a flow meter were shown in Table 3 to be INR 6050 and 10,550 (USD 86 and 151), respectively. Benefits of additional water were determined to be 2.36 INR/m^3 (0.034 USD/m^3) (Dashora et al. 2019) [16] in this same catchment using the net value of increased production per cubic metre of additional water available from check dam recharge. Assuming the life of the DWRS infrastructure was either 10 or 30 years, and following the procedure laid out by Dashora et al. (2019) [16] using the same discount rate of 8%, we found that an annual volume of 382 or 250 m^3, respectively, would need to be recharged and used productively for agricultural irrigation in order to warrant the capital expense (and including flow meter (666 or 416 m^3)). These calculated economic recharge volumes are under-estimates because they neglect annual maintenance costs, such as scraping out the pit. The lowest of these numbers exceeds the maximum annual recharge recorded in 2018 and suggests that none of the DWRSs evaluated would be economically feasible (i.e., present value of benefits exceed the present value of costs). The mean recharge in 2018 was 32 m^3, suggesting that, if this was representative of mean annual recharge, the B/C ratio would be between 0.05 and 0.13 depending on the assumed life of the infrastructure and absence or presence of meters. Even the DWRS harvesting from a large catchment (V28) failed to reach this feasibility criterion. This was quite a different result than found for check dams that had a benefit/cost ratio of 4.1 [16], and therefore remain a preferred approach to recharge enhancement in this area.

6. Concluding Remarks

In this study, we evaluated the effect of direct well recharge structures (DWRS) on the groundwater level rise over the monsoon season and the quality of water in recharged wells as compared to nearby control wells. This was the first micro scale (farm level) evaluation in a semi-arid region of Rajasthan state, which is facing the problem of groundwater over-exploitation. Water quality observations were made to determine whether groundwater quality was protected.

The volume of water recharged through DWRS into individual wells during the monsoon season varied with catchment area, rainfall amount, and intensity, and in 2018, in three wells where water flow meters did not clog, these were 27, 81, and 176 m^3 per well. Using the same ratio of recharge to rainfall over the catchment area, in the same year, the other eight wells were estimated to recharge between 2 and 19 m^3. The value of average recharge for all the wells monitored in 2018 was 32 m^3. The mean rise in well water levels over the monsoon season was higher in wells with DWRS than in nearby control wells, but not significantly different. The study revealed that some wells with DWRS have shown a larger increase in water level than in control wells, and this was particularly true for one well (V28) that accounted for 50% of the total recharge to 11 wells in 2018.

Similarly, monitoring of water quality revealed no significant difference between DWRS and control wells for pH, EC/TDS, turbidity, or fluoride. The presence of *E. coli* in DWRS wells was higher than in control wells, however, E. *coli* exceeded drinking water guidelines in all sampled wells. Values of pH, EC/TDS, and F decreased in DWRS and control wells as each monsoon progressed, whereas the turbidity of wells with DWRS increased slightly. The turbidity and *E. coli* values suggest that DWRS should not be attempted in or near wells that could be used for drinking water supplies.

The high proportion of both DWRS and control wells that failed to meet BIS criteria for drinking water suggests that well-head protection measures are needed, such as parapet walls and covers, in order to reduce these contaminant loads for wells that are used as a source of drinking water. As a result of this study, trials are commencing to monitor the changes in water quality due to well-head protection measures in the treated wells and control wells, in order to provide the evidence base necessary to inform appropriate actions by the village communities.

The volume of water recharged by DWRS was too small to warrant the expenditure on DWRS, even for the system with a very large catchment, on the basis of a present value analysis and assuming the asset life of the DWRS system is between 10 and 30 years and neglecting maintenance costs.

It is anticipated that pit filters would need to be removed, cleaned, and replaced periodically to enable DWRS to remain operational. Diverting the first flush runoff in a monsoon before water enters the filter pit, until after vegetation cover is established and turbidity reduces, would be expected to reduce maintenance needs at the cost of a reduced harvest. It is also expected that improved watershed management such as contour banking will improve quality of runoff and reduce the needed frequency of desilting of filters. It may also be a more effective form of increasing recharge than DWRS, but it would be difficult to measure recharge increase as a result of such dispersed recharge methods.

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References

1. Seckler, D.; David, M.; Randolph, B. *Water Scarcity in the 21st Century, Research Report*; International Water Management Institute: Colombo, Sri Lanka, 1999.
2. Shah, T. *Taming the Anarchy: Groundwater Governance in South Asia*; Routledge: New Delhi, India, 2009.
3. CGWB. *Report on Ground Water Scenario in India (Premonsoon 2017)*; Central Ground Water Board: New Delhi, India, 2017; pp. 1–142.
4. Cavelaars, J.C.; Vlotman, W.F.; Spoor, G. Subsurface Drainage System. In *ILRI Publication 16*; Ritzema, H.P., Ed.; International Institute for Land Reclamation and Improvement: Wageningen, The Netherlands, 1994; p. 827.
5. Massuel, S.; Perrin, J.; Mascre, C.; Mohamed, W.; Boisson, A.; Ahmed, S. Managed aquifer recharge in South India: What to expect from small percolation tanks in hard rock? *J. Hydrol.* **2014**, *512*, 157–167. [CrossRef]
6. Burke, J.J.; Moench, M.H. *Groundwater and Society: Resources, Tensions and Opportunities. Themes in Groundwater Management for the Twenty-First Century*; Department of International Economic and Social Affairs, Statistical Office, United Nations: New York, NY, USA, 2000.
7. Dillon, P.; Fernandez, E.E.; Tuinhof, A. Management of Aquifer Recharge and Discharge Processes and Aquifer Storage Equilibrium. IAH Contribution to GEF-FAO Groundwater Governance Thematic Paper 4. 2012. Available online: www.groundwatergovernance.org/resources/thematic-papers/en/ (accessed on 21 February 2020).
8. Maheshwari, B.; Varua, M.; Ward, J.; Packham, R.; Chinnasamy, P.; Dashora, Y.; Dave, S.; Soni, P.; Dillon, P.; Purohit, R.; et al. The role of transdisciplinary approach and community participation in village scale groundwater management: Insights from Gujarat and Rajasthan, India. *Int. Open Access J. Water* **2014**, *6*, 3386–3408. Available online: http://www.mdpi.com/journal/water/special_issues/MAR (accessed on 31 March 2020). [CrossRef]
9. Jadeja, Y.; Maheshwari, B.; Packham, R.; Hakimuddin, B.; Purohit, R.; Thaker, B.; Dillon, P.; Oza, S.; Dave, S.; Soni, P.; et al. Managing aquifer recharge and sustaining groundwater use: Developing a capacity building program for creating local groundwater champions. *Sustain. Water Resour. Manag.* **2018**, *4*, 317–329. Available online: https://recharge.iah.org/thematic-issues-journals (accessed on 31 March 2020). [CrossRef]

10. Dashora, Y.; Dillon, P.; Maheshwari, B.; Soni, P.; Dashora, R.; Davande, S.; Purohit, R.C.; Mittal, H.K. (2018). A simple method using farmers' measurements applied to estimate check dam recharge in Rajasthan, India. *Sustain. Water Resour. Manag.* **2018**, *4*, 301–316. Available online: https://recharge.iah.org/thematic-issues-journals (accessed on 31 March 2020). [CrossRef]
11. CGWB. *Manual on Artificial Recharge of Ground Water*; Government of India, Ministry of Water Resources, Central Ground Water Board: Shillong, India, 2007.
12. Rainwater Harvesting Association. Available online: www.rainwaterharvesting.org (accessed on 23 February 2020).
13. Bali Water Protection Program-Penyelamatan Air Tanah Bali–Annex 2-Aquifer Recharge Technical Overview. (no date). Available online: https://www.idepfoundation.org/images/idep/how-you-can-help/support-a-project/bali-water-protection-program/bwp_annex2_technical_brief_overview.pdf (accessed on 23 February 2020).
14. Pendke, M.S.; Asewar, B.V.; Waskar, D.P.; Gore, A.K.; Samindre, M.S. Openwell and Borewell Recharge Technology. In *All-India Co-ordinated Research Project for Dryland Agriculture*; Vasantrao Naik Marathwada Krishi Vidyapeeth Parbhani: Maharashtra, India, 2017; p. 20. ISBN 978-93-85456-19-0. Available online: https://www.researchgate.net/publication/319553655_Openwell_and_Borewell_Recharge_Technology (accessed on 23 February 2020).
15. CGWB. Report on Groundwater Scenario, Udaipur District, Rajasthan, Ministry of Water Resources, Central Ground Water Board, Western Region Jaipur. 2013. Available online: http://cgwb.gov.in/District_Profile/Rajasthan/Udaipur.pdf (accessed on 5 November 2019).
16. Dashora, Y.; Dillon, P.; Maheshwari, B.; Soni, P.; Mittal, H.K.; Dashora, R.; Singh, P.K.; Purohit, R.C.; Katara, P. Hydrologic and cost benefit analysis at local scale of streambed recharge structures in Rajasthan (India) and their value for securing irrigation water supplies. *Hydrogeol. J.* **2019**, *27*, 1889–1909. [CrossRef]
17. BIS (Bureau of Indian Standards). *Specification for Drinking Water IS 10500: 2004*; BIS: New Delhi, India, 2004. Available online: https://www.indiawaterportal.org/sites/indiawaterportal.org/files/drinking_water_standards_bis_10500_2004_by_bis.pdf (accessed on 31 March 2020).
18. Dillon, P.; Vanderzalm, J.; Sidhu, J.; Page, D.; Chadha, D. (2014). A Water Quality Guide to Managed Aquifer Recharge in India. CSIRO Land and Water and UNESCO Report of AusAID PSLP Project ROU 14476. Available online: https://publications.csiro.au/rpr/pub?pid=csiro:EP149116 (accessed on 23 February 2020).
19. NRMMC, EPHC, NHMRC. *Australian Guidelines for Water Recycling, Managing Health and Environmental Risks, Volume 2C–Managed Aquifer Recharge*; Natural Resource Management Ministerial Council, Environment Protection and Heritage Council National Health and Medical Research Council, NWQMS: Canberra, Australia, 2009; p. 237. Available online: http://www.waterquality.gov.au/guidelines/recycled-water (accessed on 31 March 2020).
20. Baveye, P.; Vandevivere, P.; Hoyle, B.L.; De Leo, P.C.; de Lozada, D.S. Environmental impact and mechanisms of the biological clogging of saturated soils and aquifer materials. *Crit. Rev. Environ. Sci. Technol.* **1998**, *28*, 123–191. [CrossRef]