A simple method using farmers' measurements applied to estimate check dam recharge in Rajasthan, India

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Abstract: Since the 1960s more than 200,000 check dams have been constructed on ephemeral streams in India to enhance groundwater recharge and help sustain irrigation supplies. While many farmers, non-government- and government organisations attest to check dam effectiveness very few (<30) have been quantitatively evaluated and results have been variable. The paper describes the application of a simple daily water balance calculation to four check dams near Udaipur in southern Rajasthan where farmers took daily measurements of check dam water levels and rainfall for two years. The farmer measurements were proven to be highly reliable. They revealed that the check dams augmented recharge by 33mm in 2014 an "average" year and by 17mm in 2015, a "dry" year (where recharge is expressed as depth over the combined catchment area of the check dams). This corresponded to 2.0 and 1.0 times the combined capacity of these check dams in those years, and the average annual recharge volume, 743,000m^3 supports 16% of agricultural production in the rabi (winter) season from the surrounding villages. Total recharge was estimated to be 37% and 70% of combined runoff in 2014 and 2015, respectively. Mean dry weather infiltration rates averaged from the four sites over both years were 5 to 8 times the evaporation rate from check dams. Hence, based on farmer measurements, it is conclusive that the studied check dams are effective and efficient in recharging the local aquifer. The paper demonstrates that a simple method can be used by farmers with basic training to determine the need for desilting of check dams in the following dry season and to provide essential data to allow quantification of recharge from check dams. This opens the possibility of scaling up by orders of magnitude the number of check dams evaluated. With more check dams monitored over longer periods, quantitative data would become available to inform on sizing and placement of check dams in relation to local benefits, capital and maintenance costs and downstream impacts, and thereby to inform future investment in check dams.

Keywords: Managed aquifer recharge; Water balance; Surface water-groundwater interactions; Rainwater harvesting.

1. Introduction

India has made extensive use of groundwater for irrigation in hard rock areas that occupy 65% of the Indian land-mass. Typically, these supplies are from unconfined aquifers with low specific yield and are replenished during the monsoon season and drawn down over the winter (rabi) season by pumping from dug wells established in the 1950's to 1970's, and also from deeper tube wells built subsequently. They support village water supplies and irrigation of crops. In Rajasthan, India's driest state, 91% of drinking water and 60% of irrigation water are derived from groundwater (CGWB 2012) and so it plays a vital role in the livelihood of village communities. Consequently in many areas mean annual ground water extraction has exceeded mean annual ground water recharge leading to longer-term decline in storage (Burke and Moench 2000). Therefore, in the absence of effective local groundwater demand management, government, non-government organizations and farmers since the 1960s have established check dams in ephemeral streams along with other watershed management improvements to augment groundwater recharge, buffer against storage decline and increase resilience of their livelihoods (Tuinhof *et al.* 2013). Dillon *et al.* (2009) reported on Indian cases where such managed aquifer recharge reduced the groundwater deficit by between 2% and 60%. Check dams follow well-established traditional practices to detain runoff during the monsoon allowing greatly increased time for infiltration (CGWB 2013). There is a large unknown number of check dams in Rajasthan, and in neighbouring Gujarat there are more than 75,000 of these streambed structures (CGWB 2013) and estimated to be well in excess of 200,000 in hard rock areas of India, including in Maharashtra, Madhya Pradesh, Telangana and Tamil Naidu.

Check dams are expected to have site-specific recharge effectiveness depending on runoff and the proportion that is captured, morphology, sedimentation, hydraulic conductivity of alluvium, the nature of the connection between the pooled water and the aquifer, the hydraulic characteristics and storage capacity of the aquifer and ambient groundwater quality. To understand the overall effectiveness of check dam implementation programs a very large number of check dams would need to be evaluated. For farmers and villages, evaluation of their local check dams in their current condition is important to prioritize and schedule desilting and other maintenance. For both these reasons there needs to be a simple method that can be used by farmers, with basic technical training and support, enabling wide-spread adoption. This paper describes such a method and demonstrates its application in assessment of recharge effectiveness for four check dams monitored by farmers over two years (2014-15) in the Dharta catchment of the Aravalli Hills in Udaipur District of Rajasthan. This work is part of a larger project that also addresses managing groundwater demand through better informed farmers capable of assessing groundwater availability for rabi crops and developing cooperative local groundwater management (Maheshwari *et al.* 2014).

2. Materials and Methods

2.1 The study area

Dharta watershed of the Bhinder block (an administrative district) was selected as a study area due to existing engagement of project partners and willingness of local community to participate and proximity to organizations to provide scientific and technical support. The watershed is situated at an altitude 470m above sea level at a latitude of 24º 37′ to 24º 39′ N, and longitude 74º 09′ to 74º 15′ E in about 65 km east of the city of Udaipur within the Udaipur District of Rajasthan (Figure 1). The 44 years (1973-2016) average annual rainfall at Vallabhnagar, Udaipur (17 km from Dharta catchment) is 665mm and most of it (more than 90%) falls during the monsoon season of June to September. The temperatures in the area range between 19° and 48°C during summer and 3° to 28°C in winter. Soils have a sandy loam texture and are typically one meter deep overlying granitic gneiss that can be weathered up to a depth of 28m. The area undulates with an average slope of around 2% with well-developed drainage. The watershed is situated in an administrative area of Udaipur where groundwater extraction exceeds sustainable yield (CGWB 2010).

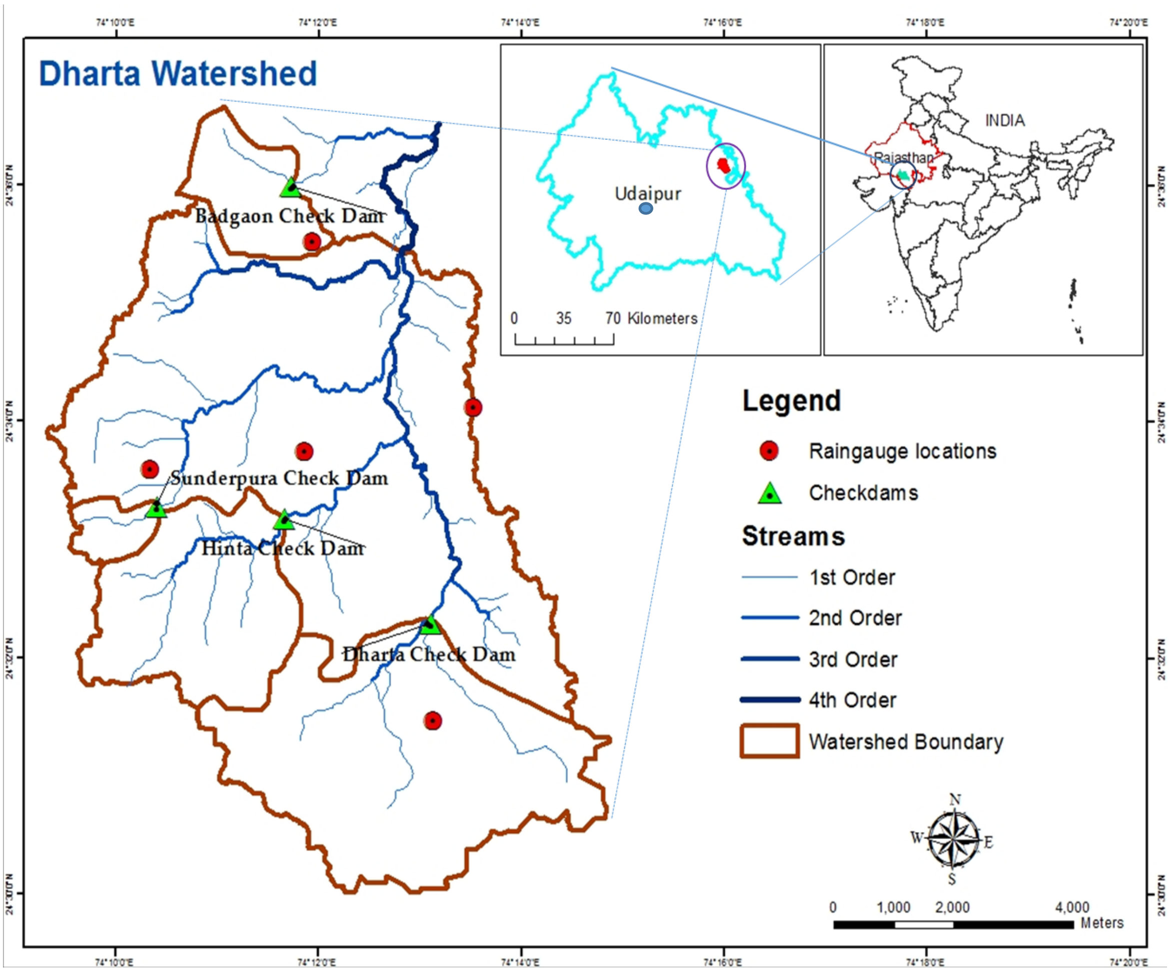


Figure 1. Location map of the study area and catchments and locations of the four selected check dams (Badgaon, Dharta, Hinta and Sunderpura) and locations of rain gauges used for water balance calculations.

2.2 Methodology

2.2.1. Selection of check dams for investigating recharge

The study was conducted on four existing check dams in the Dharta watershed one at each of four villages; Badgaon, Dharta, Hinta and Sunderpura shown in Figure 1. The check dams were representative of the size of structures in this area and had catchment areas between 109 and 1705 Ha, on streams of different order and were selected for convenience of access for daily water level measurements. The groundwater levels in nearby wells (3 wells for each structure) were also measured daily during ponding and weekly throughout the rest of the year. A water balance approach, as proposed by Dillon (1983), was used to estimate the volume of recharge contributed to groundwater by each structure for two years (2014 and 2015).

A gauge board was painted on the upstream face of the side wall of the weir to allow water level measurements (Figure 2). Zero on the gauge board coincided with a concrete apron on the upstream support for the weir. For upscaling tomany check dams it is suggested that a gaugeboard stencils be used to quickly and accurately paint these gaugeboards and where weir pools are deep to also install manufactured gaugeboards on posts at lower elevations.

Infiltration tests using double ring infiltrometer were performed by agricultural engineers in two check dams using the technique described by (Bouwer 1963). These results were subsequently compared with infiltration rates calculated from measured declines in check dams water level during dry weather.

The catchment area of each check dam was derived using the Indian Government's digital elevation map provided by the National Geophysical Research Institute, to which Arc-SWAT and

Arc GIS 10.1 were applied (Olivera *et al.* 2006) in a semi-automated procedure. Pour points (locations for which the contributing area is calculated), were specified at the outlet of each check dam. This method is a potentially more objective, repeatable, cost-effective, and consistent with other digital data sets than manual delineation. The automated extraction of topographic parameters from DEM is recognised as a viable alternative to traditional surveys and manual evaluation of topographic maps, particularly as the quality and coverage of DEM data increases (Qamer *et al.* 2008).

2.2.2 Area- and volume- elevation relationships

A topographic level survey was performed for the impoundment area of each check dam by qualified operators using a dumpy level or a theodolite ("total station") and used to calculate the area-elevation curve and volume-elevation curve of the impoundment. This is required to calculate recharge volumes, but is not required to measure dry weather infiltration rates used to determine the need for de-silting.

Before the 2015 monsoon the surface of the impoundment of each of two check dams was scraped to remove silt with the intention to enhance infiltration rate. This made a very small change to the volume of these check dam impoundments, and this was accounted for in the volume-elevation curves used for calculation of water balance components. Badgaon check dam was scraped by manual labour and Dharta by mechanical scraper. The volume of excavation was estimated by counting the number of tractor trollies of silt removed and multiplying by the contractor's estimate of the volume of silt per trolley. The dumpy level survey was subsequently repeated.

The area of ponded water was calculated by plotting a contour map from survey data. The area of the water surface at each contour level was calculated using graph paper and by planimeter. The volume contained between contours was calculated by the Trapezoidal Rule (Eq. 1).

$$\mathrm{V} = \frac{1}{6}(\mathrm{A_0} + 4\mathrm{A_m} + \mathrm{A_t})\,(\mathrm{RL_t} - \mathrm{RL_0}) \qquad \ldots(1)$$

where, V = volume in between contours, (m^3);

A_0, A_m, A_t = Area of three contours at bottom, middle and top of an interval (m^2);

RL_t = Reduced Level of top contour (m) and;

RL_0 = Reduced Level of bottom contour (m).

Below the lowest contour within the impoundment, the available storage volume of water was calculated from the cone formula (Eq. 2)

$$\mathrm{V} = \frac{1}{3}\mathrm{A\,h} \qquad \ldots(2)$$

where,

V= Volume of cone (m^3);

A= Surface area of lowest contour in the impoundment (m^2);

h = depth of lowest point in the impoundment below the lowest contour (m);

The area-elevation and area-volume curves were plotted using the gaugeboard readings corresponding to contours. The area and volume associated with any water level measured at the gaugeboard was calculated by interpolating using the Match and Index functions of Microsoft Excel.

2.2.3. Field monitoring

In this study, participatory monitoring for water level data collection was used to support community engagement (Maheshwari *et al.* 2014) and to demonstrate the viability of this method with farmers making the water level measurements. Rainfall data were recorded daily in each village (using raingauges and on some occasions, a semi-automatic tipping bucket pluviometer) around 1km distance from structures.

Training was conducted for farmers on measurement of water levels of MAR structures along with selected wells. This training consisted of basic camera operation, observation of groundwater levels using measuring tapes and check dam stage monitoring. The nominated farmers are known as Bhujal Jankaar's or BJ's (groundwater knowledge broker) and were supported as part of the MARVI project (Maheshwari *et al.* 2014). Observations were taken for the monsoon season of 2014 and 2015 and continued while the water remained in the structure. Monitoring was started on the day of the first heavy rainfall event at the onset of the monsoon; when runoff water pooled in the structures. The data was checked for its quality by regular monitoring and daily photographs of MAR structures with embedded time and date information, were also captured by some BJ's using camera and mobile phone to verify and build confidence in their water level readings (Figure 2). Results of this comparison are shown later.

Figure 2. A photograph of the Badgaon check dam water level measuring gauge (taken by BJ Radheyshyam Ji-Village Badgaon) with water level exceeding check dam crest level.

In addition to daily rainfall and check dam water level recording, BJs also measured water levels weekly in 250 wells in this proximity and for three selected wells near each monitored check dam groundwater levels were monitored daily during the period when water was pooled. BJ groundwater level data were verified by a BJ facilitator taking an independent reading if one of 10 wells at random for each BJ each week. Rain-gauge readings were not verified.

2.2.4. Water balance calculation

Recharge from check dams was calculated using a water balance approach as given in Eq. (3). In this case study, water stored in the check dam is not pumped for irrigation or any other purpose and therefore, the alteration in volume was considered due to infiltration and evaporation. The change in storage of a recharge structure is equal to the difference between the sum of all inflows and the sum of all losses on daily basis. Accordingly, the daily water balance can be written as:

$$\Delta V = V_i - V_{i-1} = Q_{in} - Q_{out} - 0.5 * (A_{i-1} + A_i) * (R_i + E_i - P_i) - U_i \quad \ldots (3)$$

where:

V_i is the volume of water stored in the morning of day, i, at the time the level is read (m^3);

V_{i-1} is volume of water stored in the morning of the previous day, i – 1 (m^3);

Q_{in} is the volume of inflow to the check dam over the day until the level is read (m^3);

Q_{out} is the volume of spill from the check dam plus any leakage downstream over the day until the level is read (m^3);

A_{i-1} is the surface area of the water in the check dam on the preceding day, i-1 (m^2);

A_i is the surface area of the water in the check dam on day, i (m^2);

R_i is the daily recharge from the check dam assumed equal to infiltration (m);
E_i is the daily evaporation from the check dam (m);
P_i is the daily rainfall on the check dam (m); and
U_i is the daily direct use from the check dam (m^3), which for these four check dams is zero.

In dry weather, the ephemeral streams in this area are dry, enabling dry weather infiltration rate to be determined from a simplified balance:

$R_i = h_i - h_{i-1} - \bar{E}$ and $\bar{R}$ is the mean of dry weather R_i … (4)

where:
h_i is the elevation of water in storage in the morning of day, i, at the time the level is read (m);
h_{i-1} is elevation of water in storage in the morning of the previous day, i–1 (m); and
$\bar{E}$ is the mean daily evaporation rate for the checkdam for the storage period (m).

For days when water level declines at less than the evaporation rate, or when water level rises but remains lower than the crest of the weir, inflow is calculated from equation (3) where R_i is set as the mean dry weather infiltration rate, $\bar{R}$ from equation (4).

Spill from the check dam is assumed to be described by the formula for discharge over a rectangular weir;

$q_{out} = C_d\, B\, H^{1.5}$ … (5)

where:
q_{out} = discharge over the crest of the weir ($m^3\ s^{-1}$);
C_d = coefficient of discharge ($m^{0.5}\ s^{-1}$) = 1.6;
B = length of the weir crest (m);
$H = h - h_{ctf}$ = height of water surface upstream of the weir, h, above the height of the cease to flow (the crest) of the weir, h_{ctf} (m); and
Q_{out} is the integration of q_{out} over the day (m^3). In the case of single daily readings;

$Q_{out} = 0.5 * 86400\ (q_{out\,(i-1)} + q_{out\,(i)})$ … (6)

Inflow to the check dam was determined from the water balance (equation 3) and considered more reliable on days of no spill for these check dams, than attempting to calibrate a rainfall-runoff model as done by Boisson *et al.* (2014) for a very large percolation pond. Runoff coefficient could be calculated for days with no spill, but due to spatial variability of rainfall over the catchment, this coefficient has not been recursively used in water balance calculations.

The weir formula could not be calibrated for any of the check dams in this study, due to practical and safety issues. A value of C_d of 1.6 was adopted based on Hamill (2011) recognizing this is a crude approximation. Another complication is that daily calculated values of instantaneous spill rates are also unlikely to yield reliable estimates of daily spill volumes in streams where flow rates can be quite variable. (A water level monitoring sensor may be deployed to provide continuous level measurements for research purposes, but not for widespread application to check dams.) Hence, calculations of inflow and spill, during times of spill should be regarded as having considerable uncertainty. For this reason, they were not used for calculation of recharge.

This water balance method assumes that the calculated dry weather infiltration rate (from Eq. 4) applies throughout both dry and wet periods for the surface area of impounded water, as in Equation (3). This underestimates the volume of infiltration during wet periods as it would be expected, following the Green and Ampt equation (Green and Ampt 1911) that sorption as well as advection of water would occur in the wetting perimeter of the rising water level in the impoundment, and that the head gradient driving infiltration would increase. According to Reeder *et al.* (1980), infiltration rates with changing surface water column depth depend on surface water depth and depth of saturated zone**.** It is also assumed that all water infiltrated becomes aquifer recharge. This neglects remnant soil moisture that evaporates before it can percolate to below the zero-flux plane below which it would ultimately become groundwater recharge. These two assumptions are expected to counter-balance each other to an extent, giving a relatively reliable estimate for recharge based on minimal data and avoiding reliance on the spill calculation. In the absence of accurate alternative measurements of recharge with which to compare these recharge estimates, this approach has been applied.

There are also other complications not considered in this assessment, including that inflowing water is turbid and silt accumulates in the floor of the impoundments, unless scoured by subsequent high flow events. Accumulation of silt is expected to reduce infiltration rate over time and this is observed to an extent in variations in the calculated dry weather infiltration rate, R_i, through the monsoon season. A further complication is that if groundwater level rise beneath the check dam results in hydraulic connection, the rate of recharge would noticeably decrease (e.g. Dillon and Liggett 1983), and therefore lower the mean dry weather infiltration rate. While this affect may result in further underestimating recharge on wet days early in the season (before hydraulic connection), in the interest of simplicity and without data on evaporation of infiltrated water during the check dam drying phase, it is assumed that the impact on estimated recharge is acceptable. Measurement of water levels in check dams could also be influenced by wind, with ripples of 2-3cm amplitude occasionally reported. Gaugeboard readings were recorded by farmers to the nearest centimeter. If greater accuracy became important, say in large area check dams a stilling well could be incorporated, but for the four monitored check dams this was an infrequent and small issue.

Evaporation was not measured within the catchment, but at Udaipur the mean annual evaporation from an A class pan from 1982 to 2010 was measured to be 5.5 mm. In Udaipur a high mean daily rate of evaporation (9 mm/d) is observed in the period March to June when average temperatures range from 33 to 40 degrees C, but over the period August to January, when check dams typically hold water, the mean temperature is lower (24 to 30 degrees C) and mean evaporation rate ranges from 5.4mm/d during the monsoon to 3.3mm/d during winter (Rao *et al.* 2012). Commonly a factor of 0.6 to 0.8 is applied to A-class pan measurements to represent evaporation from lake surfaces, to compensate for the larger area of evaporation and hence reduced advection of heat and lower humidity of air over the evaporating water surface. For this study, a uniform mean daily evaporation rate of 5mm is assumed to apply to water in check dams.

When water level in the check dam dropped below the zero reading on the gaugeboard at the end of the monsoon, the residual water in storage was partitioned into recharge and evaporation in proportion to the calculated mean dry weather infiltration rate and the evaporation rate, respectively. There was no lower level gaugeboard to determine whether infiltration continued at the same rate, and this could be a useful addition for sites intended for use as reference check dams for local groundwater and catchment management.

2.3 Previous studies of recharge from check dams

Managed aquifer recharge studies have involved numerous methods for evaluating recharge from surface water infiltration systems. The most common in India have used surface water and groundwater balances; (Sukhija *et al*. 1997; Gale *et al.* 2006; Sharda *et al*. 2006; Perrin *et al.* 2009; Glendenning and Vervoort 2011; Boisson *et al.* 2014; Massuel *et al*. 2014; Abraham and Mohan 2015; and Parimalarenganayaki and Elango 2015. Other approaches, used in India or elsewhere are; environmental chloride tracer techniques (Sukhija *et al*. 1997; Boisson *et al.* 2014); sulphur-isotopes (Clark *et al.* 2014); excess oxygen (Hershey *et al*. 2007); anthropogenic trace organics (Henzler *et al*. 2014), and use of calibrated groundwater models (Richter *et al.* 1993;Boisson *et al.* 2014; Ringleb *et al.* 2016).

For check dams and percolation tanks, that typically have variable source water quality and intermittent inflow, the dominant recharge estimation method was by calculating a water balance from the storage change in the ponded water. (A check dam is simply a weir in the stream channel, whereas a percolation tank involves an embankment to detain water together with a spillway for discharging excess flow downstream. Hence percolation tanks are generally larger and deeper than check dams.) In the studies identified above, the methods to estimate recharge converged during dry weather but diversified in wet weather. There were also contrasts in relating infiltration and recharge. These methods and their results are discussed later in this paper.

3. Results

3.1. Check dam water spread area, capacity and catchment area

The water spread area and capacity of each check dam at the cease-to-flow water level and catchment area were calculated using the methods previously described and are shown in Table 1.

Table 1. Check dam dimensions in relation to catchment area

	Recharge structure	Total depth#, m	Water spread area##, m^2	Capacity##, m^3	Catchment Area, Ha	Check dam area## as % of catchment	Check dam capacity## as mm over catchment
1	Badgaon	1.57	39,000	*42,000	338	1.15	12.4
2	Dharta	1.82	136,600	*140,000	1705	0.80	8.2
3	Hinta	2.62	127,200	223,000	851	1.49	26.2
4	Sunderpura	2.05	62,800	64,400	109	5.77	59.1

depth from weir crest to contrete apron at stream bed level which is the base of gaugeboard

calculated from area- and volume- elevation curves when water elevation is at weir crest

* mean of pre- and post-scraping volumes

The area- volume-elevation curves of Badgaon and Dharta were calculated before and after desilting, showing that volume increased at Badgaon by 4% and Dharta by 1.4% of the capacity. The curves for Dharta check dam are shown in Figure 3.

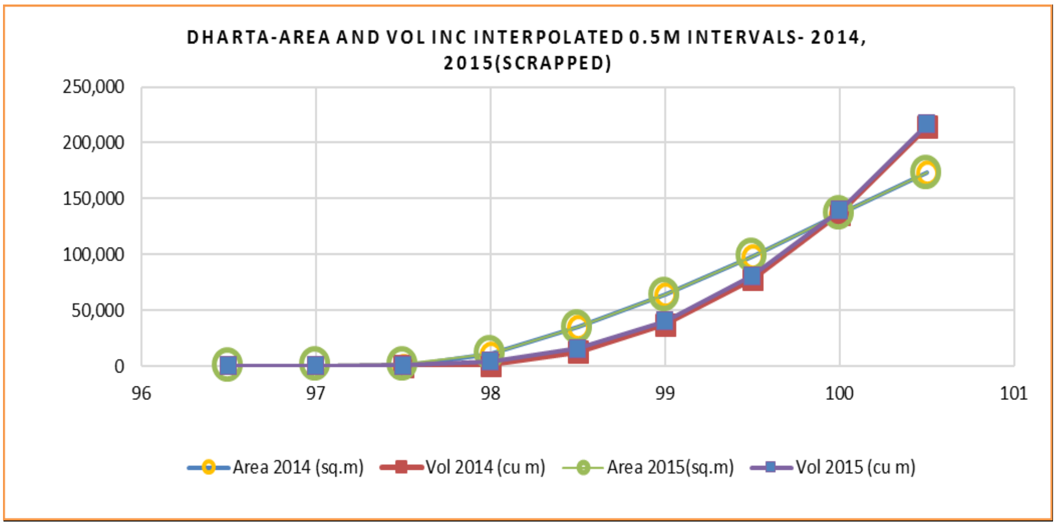


Figure 3. Area-volume v/s elevation curve of Dharta check dam before and after scraping of silt.

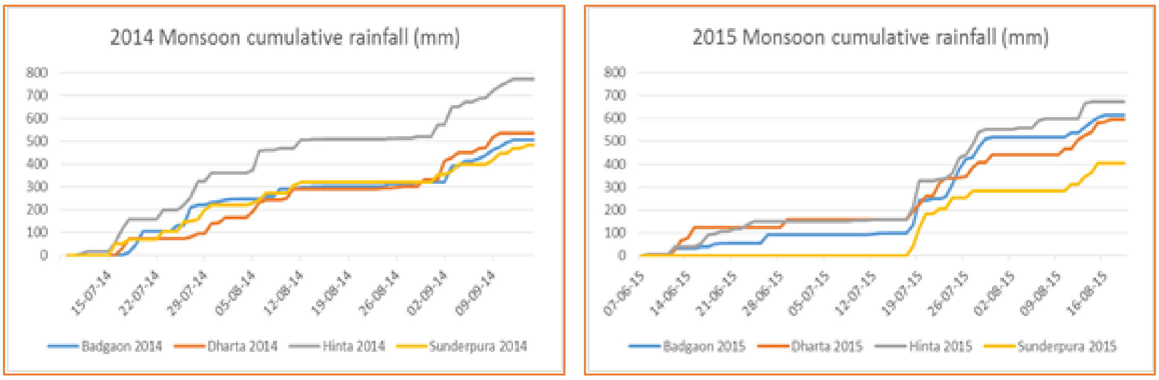
Due to observed inaccuracy of available digital elevation maps, crest level was arbitrarily assigned a reduced level (RL) of 100.00 m for each check dam.

3.2. Rainfall

Rainfall occurs in tropical storms and its distribution in this area is erratic in nature and varies spatially for each storm. The amount of rainfall received and number of rain days at each village in each year is recorded in Table 2, and the temporal pattern in cumulative rainfall is shown in Fig 4.

Table 2. Rainfall and number of rainy days in year 2014 &2015

Village	Rainfall 2014, mm (Rainy days)	Rainfall 2015, mm (Rainy days)
Badgaon	505 (30)	614 (23)
Dharta	535 (24)	596 (22)
Hinta	771 (27)	673 (28)
Sunderpura	485 (20)	406 (10)
Mean	***574 (25)***	***572 (21)***



(a) (b)

Figure 4. Cumulative rainfall at gauges in villages closest each check dam in years (a) 2014 and (b) 2015.

The four study sites are shown in Figure 5 during the monsoon season of 2015. In 2014, there was spill from all check dams except Sunderpura, but in 2015, where there was similar rainfall but at a lower intensity, only one check dam, Badgaon, spilled.

i) Badgaon check dam

iii) Hinta check dam

ii) Dharta check dam

iv) Sunderpura check dam

Figure 5. Photos of the four check dam structures during the 2015 monsoon season.

3.3. Water level variations and water balance at recharge structures

Water level fluctuation of the four structures were measured by farmers over two monsoon seasons. The accuracy of these readings at Hinta was checked using photographs of the gaugeboard taken by the farmer at the same time he recorded his observation. The comparison of results shown in Figure 6 reveals that of 187 readings over a range of 2.7m, 96% of readings were within +/- 1cm and 98% were within +/- 2cm of the value read from the photograph. The largest discrepancy, -8cm occurred at the highest level during turbulent flow over the weir. The regression had an R^2 exceeding 0.999. Considering that the wind ripple effect on some occasions was observed to be around 1-2cm amplitude, this gives great confidence in the reliability of readings of this farmer and suggests that the training provided in the BJ program was highly effective in this case. Taking photographs is valuable for data quality assurance.

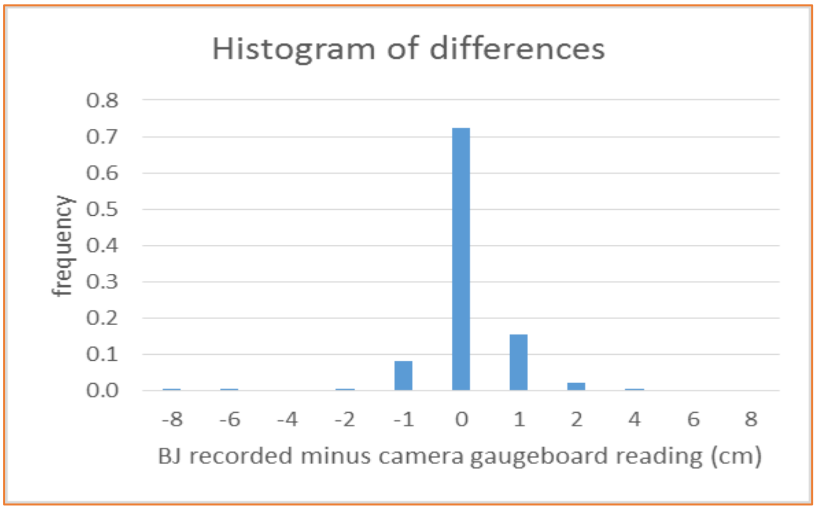


Figure 6. Histogram of differences between farmer-recorded check dam gaugeboard readings and values read from concurrent farmer photographs by a university researcher. N= 187.

These water levels were used in calculations and the resulting water balance components are tabulated in Tables 3a and 3b and shown in Figure 7. In contrast, researchers installed a pressure transducer and data logger in each check dam, particularly aiming to record water level during spill, but due to equipment failure no useable data were retrieved. Across all check dams and both years, rainfall ranged from 405mm to 771mm, and runoff is estimated to be from 13,000 to 1,312,000 m^3. These figures are considered reliable for check dams that did not spill. Individual structures captured between 27% and 100% of estimated runoff and the volume recharged was between 23% and 88% of runoff.

The total recharge volume from the four check dams in years 2014 and 2015 amounted to 976,000 m^3 and 510,000 m^3 respectively which was 2.0 and 1.0 times the total capacity of the check dams (Table 3a and Table 3b). Evaporation accounted for 4% and 25% of the total volume impounded in 2014 and 2015, respectively. The mean dry weather infiltration rate at each site ranged from 0.018 to 0.057 m/day across the sites.

Table 3a Estimation of water balance components of check dams 2014

	Recharge Structure	Rainfall, mm	Total Inflow, m3	Total Recharge, m3	Total Spill, m3	Total Evapor-ation, m3	Total Recharge/ Total Inflow, %	Total Recharge/ Capacity	Emptied
1	Badgaon	505	349,000	113,000	218,000	19,000	32%	2.86	Oct-14
2	Dharta	535	1,312,000	299,000	954,000	64,000	23%	2.19	Dec-14
3	Hinta	771	949,000	518,000	358,000	91,000	55%	2.32	Jan-15
4	Sunderpura	485	54,000	46,000	0	8,000	85%	0.71	Oct-14
	Total		**2,664,000**	**976,000**	**1,530,000**	**182,000**	**37%**	**2.02**	

Table 3b Estimation of water balance components of check dams 2015

	Recharge structure	Rainfall, mm	Total Inflow, m^3	Total Recharge, m^3	Total Spill, m^3	Total Evapor-ation, m^3	Total Recharge/ Total Inflow, %	Total Recharge/ Capacity	Emptied
1	Badgaon[1]	614	189,000	56,000	129,000	4,700	27%	1.34	Aug-15
2	Dharta[1]	596	192,000	157,000	0	44,000	81%	1.12	Nov-15
3	Hinta	673	331,000	286,000	0	63,000	86%	1.28	Nov-15
4	Sunderpura	406	13,000	11,000	0	1,600	88%	0.17	Aug-15
	Total		**725,000**	**510,000**	**129,000**	**113,300**	**70%**	**1.00**	

[1] Badgaon and Dharta check dams were scraped in 2015 before the monsoon

Figure 7. Water balance plots for four check dams - Badgaon, Dharta, Hinta and Sunderpura, in years 2014 and 2015. Each plot shows rainfall and storage volume history in the check dam. The flux components are shown as cumulative volumes; inflow, spill (if any), recharge and evaporation. The dashed line indicates the capacity of the check dam (that is the volume above which spill would occur).

3.5 Comparison of recharge sites

As shown in Table 3a the annual recharge of separate check dams ranged from 11,000 to 518,000m³ in 2014 and 2015. The Hinta check dam, with largest capacity and second highest ratio of capacity to catchment area (26mm, Table 1), had the largest recharge volume of the four structures in both years. It had the longest duration of storage that lasted until mid-January after the 2014 monsoon. Although these structures were within the same watershed they were on separate tributaries and their inflows differed significantly. The Sunderpura structure captured 100 percent runoff in both years suggesting its designed detention capacity of 59mm over the catchment area is over-sized. The aggregated seasonal runoff coefficient was calculated for each check dam that did not spill. In the moderate rainfall year of 2014, this was 0.102 at Sunderpura. In the following 'dry' year the seasonal runoff coefficient ranged from 0.019 at Dharta and 0.029 at Sunderpura to 0.058 at Hinta. Seasonal runoff coefficient increased with magnitude of rainfall as could be expected.

The mean dry weather infiltration rate (DWIR) for year 2014 was 0.027 m/day (Table 4) and dry weather recharge contributed 80% of total recharge. In year 2015, however, the mean dry weather rate (0.048 m/day) was slightly higher but the contribution of recharge in dry weather was marginally less (74%), due to lower storages leading to shorter duration of water detention. These rates were comparable with several double ring infiltrometer tests in Hinta check dam (0.048 m/d) and in Sunderpura check dam (0.073 m/d), fortuitously so, given the observed heterogeneity of streambed sediments. The high proportion of estimated recharge derived from reliably calculated dry weather infiltration in both years gives confidence in the application of this method. Furthermore, dry weather infiltration rate, as determined, provides a useful indicator to farmers as to whether desilting is required over winter. In this case, mean rates exceed five times the evaporation rate, and if rates fall to 2 to 3 times evaporation then desilting is warranted to avoid excessive evaporative loss. Sukhija *et al.* (1997) suggested that if the water level in the check dam falls daily by more than 2 cm/day, then the check dam may be considered to be effective since daily evaporation is less than 1 cm/day. So, in this study, based on dry weather infiltration rates the check dams meet Sukhija's criterion (Sukhija *et al.* 1997).

Table 4. Dry weather infiltration rates and recharge (seasonal mean values averaged across the four check dams)

Year	Mean Dry weather infiltration rates, m/day	Average ponding duration, days	Dry weather recharge as a % of Total Recharge, %	Total Recharge, m^3
2014	0.027	129	80	976,000
2015	0.042	70	74	510,000

In Figure 8, estimated check dam recharge is plotted against runoff (with both expressed as mm of check dam catchment area) for the four check dams and both years. The Hinta structure, having the second largest catchment area and second largest capacity per unit catchment area performed well in both years with highest recharge volume and depth of recharge. It should be noted that its rainfall was also highest in both years. Dharta check dam is in a catchment twice as large, but with the smallest capacity per unit catchment area, and gave the lowest recharge rate per unit catchment area in both years. In the average year, 2014, it spilled most of its inflow, but in the dry year, 2015, spilled none. Sunderpura structure appears to be overdesigned and spilled no water in either year. Badgaon, the only structure to spill in both years, spilled about 65% inflow in each year. This may suggest potential for more recharge structures in this sub-catchment, subject to meeting water needs downstream.

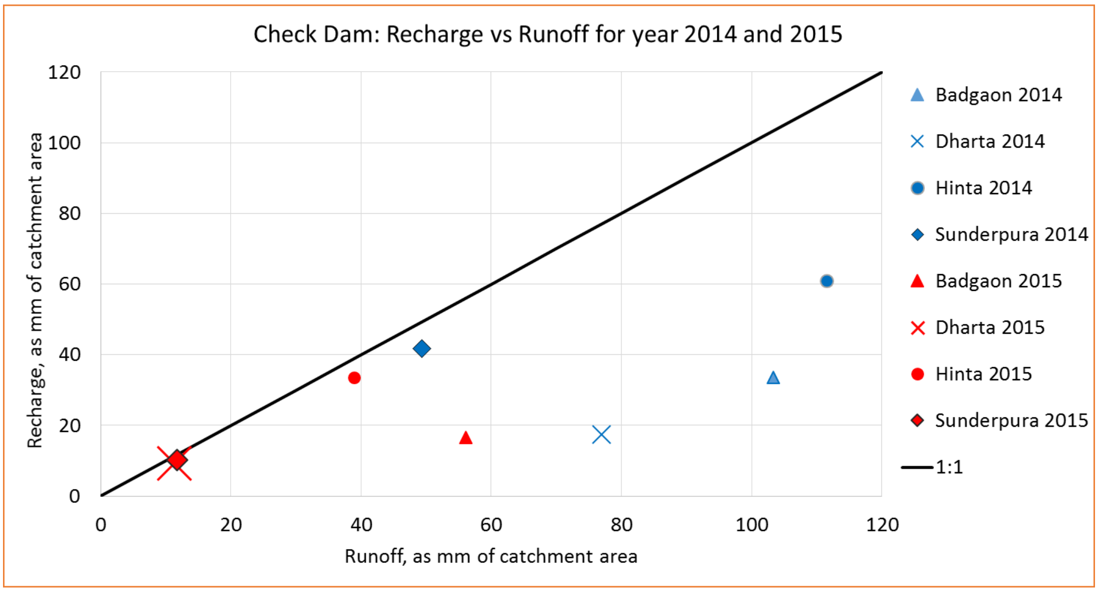


Figure 8. Relation between recharge and runoff, expressed as mm over the check dam catchment area, for the four check dams in years 2014 and 2015. The vertical separation between the 1:1 line and plotted recharge represents the sum of evaporation and spill, with spill occurring only when runoff exceeds 39 mm in either year.

3.6. Comparison between two monsoon seasons

In 2014, three structures out of four spilled water and an average of 57 per cent of runoff was captured whereas in 2015 only one recharge structure (Badgaon) overflowed and average runoff capture was 83 per cent. The ponding duration in 2014 ranged from 94 days (Sunderpura check dam) to 175 days (Hinta check dam). In 2015 ponding durations were shorter ranging from 19 days (Sunderpura) to 123 days (Hinta). Longer dry spells occurred in 2015 (as seen in Figure 4) and the intensity of rainfall was also low, resulting in low runoff and smaller storage volumes in recharge structures.

3.7 Interaction between surface and groundwater

Water levels were measured in check dams along with the groundwater elevation of nearby wells. As demonstrated for Hinta in Figure 9, rise in groundwater level commenced at around the time that ponding began in mid-July 2014, but started falling on the commencement of pumping which occurred while water remained in the pond. Three wells were selected for daily monitoring with wells H13 and H14 situated downstream (down gradient) of the structure at distances of 477m and 386 m and H34 was 315 m upstream of the structure. Groundwater level in H13 rose to within 2m of the pond level. If hydraulic connection occurred there would be a conspicuous fall in dry weather infiltration rate (as per Dillon and Liggett 1983). As the dry weather infiltration rate did not diminish sharply during periods of high groundwater levels nor rise quickly when levels declined, it is presumed that hydraulic connection did not occur at Hinta in 2014. The wells on the downstream side of the check dam showed a more pronounced effect of recharge than the well upstream (H34). The relative contribution of diffuse recharge of rainfall, riverbed recharge and recharge from the check dam are unknown at these wells. It must not be presumed that all the observed head rise is attributable to the check dam.

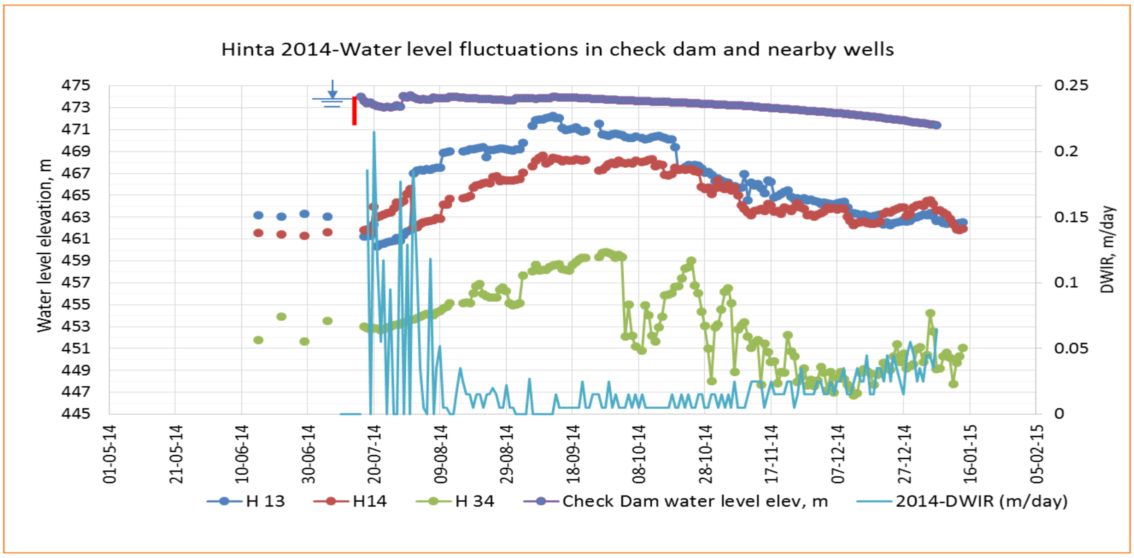


Figure 9 Relation between surface water (check dam) and groundwater (wells): Hinta 2014

4. Discussion

Selection of recharge estimation method depends on the circumstances and the required accuracy and reliability of recharge estimates (Scanlon *et al*. 2002). Recharge estimates may be refined as the frequency of observations is increased. A great advantage of farmer measurements is the ability to record daily water levels and rainfall in remote locations. It was excessively expensive to send technicians or scientists at this frequency. The alternative would be to install transducers and logging equipment that is both affordable, protectable and operable in remote locations. When pressure transducers and logging equipment was deployed in these four check dams by experienced university operatives as a backup measure and to improve accuracy of spill estimates, ultimately no valid data was retrieved due to battery failure, difficulty in setting the pressure range in the field, inability to access equipment and determine if it was operating correctly once it was submerged and limited ability to calibrate the equipment in-situ. Not only were farmers far more reliable in data collection, but they also became immersed in an understanding of how the check dam was performing and could communicate this with other farmers and contribute to the motivation for maintenance.

In this study, a water balance approach was used for hydraulic evaluation of four check dams as managed aquifer recharge structures. The total recharge contribution by the structures was calculated by balancing between inflow, outflow and losses from the structure, in such a way as to minimize anticipated uncertainties. The observations were taken on a daily basis and rely heavily on calculated dry weather infiltration rate when there was neither inflow nor spill. This study also exhibits the relationship between check dams and underlying groundwater and suggests over these two years that impoundments may be hydraulically disconnected from the underlying aquifer.

The entire runoff was harvested for three of the four check dams in the ‘dry’ year and for one of the four check dams in the ‘average’ year. For occasions when spill occurred, there is considerable uncertainty on the proportion of runoff captured. Further work is underway to assess the downstream impacts of check dams, and this may help lead to scientifically founded guidance on the size and number of recharge structures to achieve equitable benefits of water within the catchment of an ephemeral stream.

The prominent features of other work done in India on recharge estimation for check dams and percolation tanks, principally by water balance methods, are summarized in Table 5 and compared with the results obtained in this study.

Table 5. Summary of estimates of recharge from check dams and percolation tanks in India using water balance methods for all identified studies.
(Blank (-) indicates parameter was not presented and could not be derived from data contained in the reference.)

No.	Reference, location and duration of study	Rainfall, mm	Type and Size of structure, m^2	Capacity of Structure, m^3	Ratio of capacity to catchment area, mm	Method of recharge calculation in wet weather	Dry Weather Infiltration Rate (DWIR), m/d	Annual recharge as a fraction of check dam capacity	Runoff as mm of catchment area	Recharge as mm of catchment area	% of runoff recharged
1	Sukhija *et al*.(1997) Hyderabad, India 4.5 months (Nov 1992-April 1993)	-	Percolation Tank 2.5 m depth, 15,000	10,000	-	No observation in wet weather	0.007	0.33	-	-	50
2	Gale *et al*. (2006) Tamil Nadu, Maharashtra, Gujarat, India 1 year (2004-05)	753	Karanam-pettai check dam, Coimbatore, Tamil Nadu	10,200	7.2	Linearly interpolated between DWIR before and after wet period.	0.030	1.4	17	10	62
		1860	Check dam 3, Kolwan Valley, Maharashtra	-	0.03	Water level data for observation boreholes near CD3 and the specific yield of the aquifer (estimates based on pumping test data)	(ground-water was draining into the stream)	-	-	33	1
		441	Bhanavas check dam, Gujarat	21,800	1.8	Linearly interpolated between DWIR before and after wet period.	0.078	2.6	-	4.8	-
3	(Sharda *et al*. 2006) Gujarat, India 3 years (2001-2004) Study for recharge function development in 2003-04	845	2 check dam sites, (for recharge function development)	21, 500	-	Developed a function to estimate recharge from rainfall and storage depth	-	-	-	64	34

Table 5 (continued)

No.	Reference, location and duration of study	Rainfall, mm	Type and Size of structure, m^2	Capacity of Structure, m^3	Ratio of capacity to catchment area, mm	Method of recharge calculation in wet weather	Dry Weather Infiltration Rate (DWIR), m/d	Annual recharge as a fraction of check dam capacity	Runoff as mm of catchment area	Recharge as mm of catchment area	% of runoff recharged
4	Perrin *et al.* (2009) Andhra Pradesh, India Oct 2007-Feb 2008	-	1 Percolation tank	-	-	Not applicable	0.007 – 0.012	-	-	-	56
5	Glendenning and Vervoort (2011) eastern Rajasthan, India 1 year (2007-08)	449, 897, 706	3 Check dams	11,000 - 50,000	-	Recharge versus depth on dry days	0.037	-	-	-	-
6	Boisson *et al.* (2014) Maheshwaram Watershed, Telangana, India 1 year (2012-13)	604	1 Percolation tank , 4 m depth	-	-	Constant rate calculated from dry weather was applied in wet weather. Very small inflow. No spill.	0.0055	-	0.3	0.2	63
7	Massuel *et al.* (2014) Andhra Pradesh, India 2 years (2007-09)	624	1 Percolation tank	120,000	0.13	a function between percolation and depth was derived from dry weather recharge	0.002	1.3	291	179	61
8	Abraham and Mohan (2015) Tamil Nadu, India 2 years (2004-2006)	1496	Check dam, 15,000	800,000	-	Rates measured during dry weather was applied when abstraction and rainfall occurs	0.010	-	-	-	79
9	Parimalarenganayaki and Elango (2015) Arvari river, Tamil Nadu, India 2 years (2010 -2012)	1200	Check dam, 3.5 m depth	4,200,000	-	Not mentioned	0.021	1.6	-	-	63
10	Current study, Rajasthan, India Year 1: 2014	574	4 check dams (1.6-2.6 m depth)	42,000-223,000 (total 469,000)	16	Mean DWIR were applied in wet weather recharge calculation	0.027	2.0	89	33	37
	Current study, Rajasthan, India Year 2: 2015	572					0.042	1.0	24	17	70
	Median	**706**		**50,000**	**1.8**		**0.021**	**1.4**	**29**	**25**	**61**

In table 5, the accessible results from eight different studies were summarized along with the result of the current study. All studies calculated recharge using a water balance, and methods were effectively identical in dry weather but differed in wet weather. These covered 15 check dams and 4 percolation tanks widely distributed in India on hard rock terrain. The study periods were quite short, spanning from one season to two or three years. Rainfall during study years ranged from 441 to 1860mm, and in both years the check dam sites for the current study were in the lower end of this range. However, comparing ratio of check dam capacity to its catchment area, these values (averaging 16mm) from the current study were beyond the range for the other four studied check dams where values could be deduced (0.03 to 7.2mm). The larger check dam capacity per unit catchment area is expected to help compensate for the lower annual rainfalls, which generally occur in relatively few but heavy storms that generate significant runoff. The capacity of each of the check dams in the current study was comparable with other check dams albeit the mean exceeded the median size (~50,000m^3) for the sites where capacities were reported.

In the current study 74-80% of the total recharge occurred in dry weather, when the recharge estimate is considered more reliable than in wet weather. The dry weather infiltration rates varied from 2 mm/day to 78 mm/day and the median of these values from 11 studies was found to be 21 mm/d which is comparable with the results of this study (27-42mm/d). The volume of annual recharge of each check dam could be expressed as a fraction of the check dam capacity. The range in values for 7 studies was 0.33 to 2.6 with a median of 1.4, comparable with the current study where the annual range for the four check dams combined was 1.0 to 2.0. The estimated runoff, as mm of catchment area, ranged between 0.3 and 291mm, however the accuracy of some of these results depend on information that the studies did not present. The recharge as mm of catchment area varied from 0.2 to 179mm with a median value of 25mm which is similar to the values found in the current study, 17-33mm. Eleven studies contained information to enable an estimate of the percentage of inflow volume that was recharged. This varied between 1 and 79 % with the median value of 61%. Again, the values obtained from the current study 37-70% are typical of the cohort of studies for which estimates are available.

In summary, from the current study, the volume of recharge achieved by structures depended on the runoff available, the size of the impoundment and the permeability of underlying material, including any accumulated silt.

The maintenance of the structures by desilting may affect the performance of the structure and further work is warranted to understand the hydraulic and economic effectiveness of frequency of maintaining existing structures in comparison with constructing new ones. This study has demonstrated that very simple methods, capable of being used by farmers can provide sufficient information for assessing and enhancing recharge through check dams in ephemeral streams in hard rock aquifers used for irrigation supplies. The estimated recharge based on the water balance approach presented here, demonstrates that recharge enhancement from these 4 check dams contribute 743,000 m^3/year on average over these two years which is sufficient to supply water for irrigation of 186 Ha of crops for the current 1183 Ha mix of rabi crops in this area and is therefore responsible for 16% of farm income. A full cost-benefit analysis is in preparation.

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Author Contributions: YD undertook site selection, design of monitoring, and data processing and interpretation as a MARVI project officer and as a PhD student. Peter Dillon assisted with design of monitoring and analysis of data and editing manuscript drafts; Basant Maheshwari conceived and led the MARVI project and supported field work, including training of BJs and appointment and supervision of project officers and editing of the manuscript; P S undertook data collection and assisted in its compilation, BJ training and data quality assurance; R D undertook field evaluation of crop water use that enabled calculation of MAR

contribution to cropped area. Mr. Sham Davande provided training on ArcGIS and assisted with geospatial analysis; R.C Purohit and H.K. Mittal were Ms Dashora's PhD supervisors and gave helpful advice.

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