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Hydrologic and Cost–Benefit Analysis of Multiple Check Dams in Catchments of Ephemeral Streams, Rajasthan, India

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Abstract: Investment in the small-scale enhancement of groundwater recharge through check dams and other recharge structures in rural India is on the order of USD 1 billion/year. However, for any catchment, the optimal capacity of check dams is unknown, and the impacts on downstream flows are rarely determined. This paper describes a method that can be applied to plan recharge augmentation in catchments that have at least one monitored check dam. It was applied in the Dharta catchment of the Aravalli Hills in Udaipur district, Rajasthan, India, where four check dams in an ephemeral stream were monitored by farmers over seven years. For the last three years of this study, the hydrology of two of these check dams was affected by 19 new check dams established upstream. A basic hydrologic model, WaterCress, was calibrated on monitored check-dam storages and used to assess the impacts of the new structures on recharge from those downstream. Then, the model was rerun with a range of capacities of upstream check dams to determine the effects of check-dam capacity on (1) the recharge from the downstream check dam, (2) the total recharge from all check dams, and (3) the frequency of spill from the downstream check dam. Using the available economic information, the benefit–cost ratio was calculated for a range of check-dam capacities. This showed a decline in economic efficiency with each new check dam and defined the optimal capacity. Monsoon size was found to be consequential to results, and longer hydrological records yield more reliable results. The study showed that monitoring check dams, rainfall, and groundwater levels is key to deciding whether additional check dams are economically beneficial.

Keywords: water resources planning; stream hydrologic modelling; economics; dams; managed aquifer recharge; cumulative impacts; optimisation; catchment storage; participatory monitoring

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1. Introduction

Numerous studies of recharge from check dams, percolation tanks, and other recharge structures in ephemeral streams have been reported, with ten of these summarised by Dashora et al. (2018) [1]. In each case, the structure detains water to allow time for infiltration to underlying groundwater, thereby increasing groundwater recharge over that which would have occurred without the structure, especially where the stream bed is always above the water table (Bouwer 1978 [2], Dillon and Liggett 1983) [3].

There are also many references to optimising the capacity of proposed water supply dams using deterministic and stochastic modelling methods (e.g., Loucks et al. 2017) [4].

Interestingly, Booker and O'Neill (2006) [5] found in their study that the optimum economic capacity of a dam to service a given demand reduced in size as evaporation or seepage losses increased. Methods to integrate surface water planning with groundwater systems are well established, e.g., Morel-Seytoux (1977) [6]. Morel-Seytoux et al. (2016) [7] evaluated regional scale river bed seepage and Lindhe et al. (2020) [8] determined MAR potential in Botswana, using these approaches.

However, the absence of information on stream flows and seepage rates, and on the value of recoverable water, constrains the use of these methods in data-poor catchments. The authors could find no study that determined the optimal capacity of multiple check dams within a catchment or cumulative impacts of multiple recharge structures in an ephemeral stream. The development of methodology for the latter has been limited by the availability of hydrologic and economic data in data-sparse areas. This is overcome in the current study using daily rainfall and check-dam water-level data recorded by local farmers during monsoon seasons over a period of seven years at four check dams in one catchment in Rajasthan, India. This has allowed basic deterministic modelling based on these historical data in two ways. Firstly, this allows us to assess impacts of new upstream check dams on recharge and spill from established check dams downstream. Secondly, this allows us to substitute upstream check dams of different sizes into the model to determine the optimum economic capacity of check dams within the catchment using the same historical hydrological record.

The work presented here aims to inform investment in streambed recharge structures within a catchment to increase cumulative recharge, subject to the constraint of maintaining economic efficiency across the portfolio of recharge structures. It also aims to indicate the likely impact on flow downstream of the aggregation of check dams, that is, the spill from the downstream check dam. In most of India (and in some other countries) all non-committed surplus monsoon runoff is considered to be available for recharge in groundwater recharge master plans (CGWB 2020) [9]. If ecosystem requirements and sharing arrangements with downstream communities are recorded as commitments in water management plans, then this would align with the best practice for environmental flows, as described by Schofield et al. (2003) [10]. Where these concepts are adopted, they will constrain the expansion of the capacity of recharge structures in a catchment.

This paper describes the study catchment and the modelling methodology before progressing to results, discussion, and conclusions.

2. Methods

2.1. Dharta Catchment and Studied Check Dams

The value of increasing groundwater recharge using single-streambed detention structures in ephemeral streambeds has been evaluated by hydrological monitoring at four check dams over three years, 2014–2016, in the Dharta catchment of the Aravalli Hills in Udaipur district, Rajasthan, north-western India (Dashora et al. 2018) [1]. Subsequently, a cost–benefit analysis of check dams was undertaken (Dashora et al. 2019) [11] using the costs of check dams and the net value of the recharged water for agricultural production after accounting for costs of production. Following the 2016 monsoon, a very wet year, watershed management agencies constructed 19 additional recharge structures within the same catchment. Twelve of these are upstream of the studied check dam at Dharta and seven are upstream of the Hinta check dam (Figure 1). There were no new check dams installed upstream of the other two studied check dams at Badgaon and Sunderpura. Continued monitoring of rainfall and check-dam water levels from 2017 to 2020 for these four check dams presented an opportunity to assess the cumulative effects of the upstream check dams.

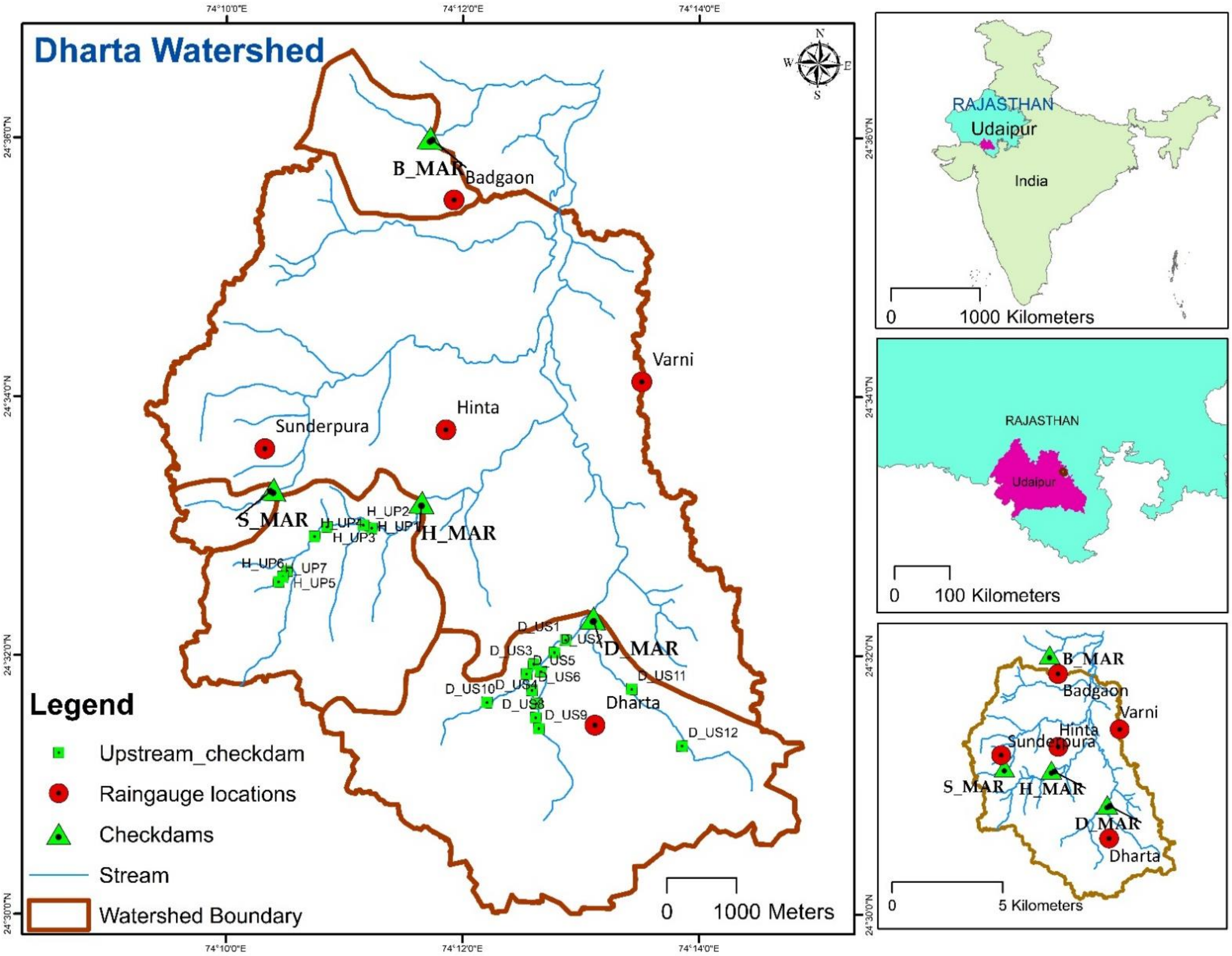


Figure 1. Map of the Dharta catchment showing the four monitored check dams and the identified check dams constructed in 2017, 12 upstream of the Dharta check dam (total capacity 67 ML) and 7 upstream of the Hinta check dam (total capacity 34 ML). 1 ML = 10^3 m^3.

This paper has four main purposes. Firstly, it presents the water balance results for the four check dams over seven years, which is twice the length of the longest hydrologic study of check dams in semi-arid areas reported in the literature (Dashora et al. 2019) [11]. The second purpose is to evaluate the cumulative impacts of the upstream check dams on (1) the recharge from the downstream check dam, (2) the total recharge of all check dams, and (3) the frequency of spill from the downstream check dam, for the two catchments now containing upstream check dams. To do this, a hydrological model, WaterCress (Cresswell and Clark 2011) [12], was calibrated for the catchment of each check dam, then used to interpret the effects of the upstream check dams. Thirdly, the calibrated model was used to explore the same three effects of expanding the capacity of upstream check dams. The intent is to show the extent to which upstream check dams reduce the recharge effectiveness of downstream check dams, increase the total check-dam recharge in a catchment, and reduce the frequency of spills, and the variations in these effects between wet and dry years. Finally, by making use of available economic information, it was possible to estimate the most economic total storage capacity of multiple check dams in these catchments, to maximize the benefit/cost ratio of total recharge from check dams.

The MARVI project (Managing Aquifer Recharge and Sustaining Groundwater through Village-level Interventions) was a project established by the Australian Centre for International Agricultural Research in partnership with Indian and Australian research organisations in 2011–2017. It has since been extended through the help of the Australian Water Partnership, to empower farmers to understand and manage their groundwater and its use to maximise returns. This involved extensive observations of rainfall, groundwater levels and check-dam levels by farmers, with quality control and interpretation of results by researchers. Consequently, farmers understood the need for participatory management of groundwater use and maintenance of recharge enhancement. Several village groundwater cooperatives were established to help achieve these goals and facilitate engagement with government entities responsible for water resources assessment and management, watershed management agencies, and agricultural production (Maheshwari et al. 2014 [13]; Jadeja et al. 2018 [14]).

The daily water balance method described by Dashora et al. (2018) [1] is based on the daily measurement of rainfall and check-dam water level and is used to estimate recharge and evaporation in dry weather and inflows in wet weather for four check dams. The spill was infrequent, and when it occurred, it was very crudely estimated from the daily gauge board reading of water level. A map of these check dams and those constructed upstream of Dharta and Hinta check dams in 2016 is given in Figure 1.

2.2. WaterCress Model Description

The hydrologic model used is WaterCress (Cresswell and Clarke, 2011) [12], which was developed initially to evaluate the impacts of farm dams on flows in rural catchments of reservoirs used for city water supplies in South Australia (Teoh 2002, 2007 [15,16]; Heneker 2003) [17]. The model has also been extended and applied to evaluate opportunities for stormwater harvesting and managed aquifer recharge in urbanising catchments under a changing climate (Clark et al. 2015) [18]. The model uses a daily time step to produce a water balance for each check dam, and more detail is given below. This was done for all seven monsoons or until the establishment of upstream check dams, and was applied to recursively calibrate a parsimonious expression for daily recharge rate. The same expression was used for all check dams, and results for seasonal recharge agreed well with those determined from each check dam by the water balance method described by Dashora et al. (2018) [1].

Hence, rather than trying to generate runoff from rainfall using the model, the model was used to simulate the storage in each downstream check dam based on the observed MARVI check-dam daily water levels, using the same volume and area relationships as determined in the MARVI project from dumpy level surveys. Inflow to the check dam was calculated by adding the rain gauge rainfall applied to the water surface area of the check dam and runoff from the catchment. Runoff was determined daily from the increase in check-dam storage volume and adding the estimated infiltration, evaporation, and any spill if the water level exceeded the crest of the check dam weir. Evaporation was estimated as per Dashora et al. (2018) [1] using a constant evaporation rate of 5 mm/d over the water surface area of the check dam. Catchment runoff was assumed to be evenly generated across the catchment area. This was then applied to the model in the absence of upstream check dams for the period 2014 to 2020 for each of the four catchments. Then, the upstream check dams were included in the model for the Dharta and Hinta subcatchments for the same total period.

Recharge estimated by the WaterCress model was calculated differently from the MARVI-derived values, where the wet-weather infiltration rate was assumed to be at the mean dry-weather infiltration rate, which could only be calculated retrospectively after the check dam had dried out each year. The MARVI-calculated dry weather infiltration rates varied day to day because of wave action on the gaugeboard, but over periods of several days, aggregates gave consistent values.

For parsimony, the method of recharge calculation adopted in WaterCress was identical for each check dam and was found by fitting simple functions until the model-calculated seasonal recharge gave the best match to recharge calculated from the MARVI check-dam water balances over the seven years of record for all check dams. It was found that infiltration rates on the first fill of each monsoon were significantly higher than the average rates for each check dam. It was also found, in very wet years, that hydraulic connection occurred between check dams and underlying groundwater, which reduced the infiltration rates in those periods (Dashora et al. 2019) [11]. The combination of these two effects in the calibrated model gave the recharge component over the water surface area of the check dam as follows:

Infiltration = 150 mm on the first fill of a check dam (1)

Infiltration rate = 20 mm/day thereafter if cumulative seasonal rainfall $\leq$ 650 mm (2)

=10 mm/day after cumulative seasonal rainfall > 650 mm (3)

The seasonal recharge calculated by both methods were compared for each check dam and year, and are presented in the results section.

This use of check-dam water level data avoided the need for a rainfall-runoff model within the WaterCress water balance model. From pluviometer records at one station over several years, it was obvious that rainfall intensity had a dominant impact on inflows, but this was unknown over most of the catchment in all years. It was also found (Table 1) that daily rainfall was highly variable over the 3003 Ha combined catchment area.

Table 1. Monsoonal rainfall (in millimetres) for five daily-read rain gauges in the Dharta catchment for the monsoons from 2013 to 2020. The average of all five stations in shown in bold.

Year	Badgaon	Dharta	Hinta	Sunderpura	Varni	Mean of Rain Gauges	COV
2013	326	333	354	191		**301**	0.25
2014	505	535	771	495	728	**607**	0.22
2015	614	596	673	406	273	**512**	0.33
2016	1161	1151	1383	1069	1194	**1192**	0.10
2017	* 525	653	675	620	728	**640**	0.12
2018	654	563	746	539	679	**636**	0.13
2019	915	926	1067	1084	858	**970**	0.10
2020	874	681	616	665	475	**662**	0.22
Mean 2013-20	**697**	**680**	**786**	**634**	**705**	**700**	0.08
COV	0.36	0.35	0.37	0.46	0.38	**0.37**	

Note: * Includes estimate for missing data.

2.3. Modelling Method for the Current Check-Dam Situation

Modelling of the Rajasthan catchments proved to be difficult, as the accuracy is constrained by the significant spatial variation in rainfall known to occur across the catchment due to convective storms with a small cell size in relation to the 51 sq km Dharta Catchment (Table 1). Year-to-year variations in monsoon rainfall were even greater. Rainfall intensity data from a pluviograph at Hinta were available only for the years 2018 to 2020, and this showed that the runoff is strongly influenced by rainfall intensity. The differences in order of magnitude between reliable runoff estimates in times of no spill could be observed on days with similar daily rainfalls. Hence, without rainfall intensity data, the use of a rainfall-runoff model with daily data could not be relied on to accurately assess the impact of upstream dams. The assumptions adopted in WaterCress modelling are shown in Table 2.

Table 2. Assumptions adopted in WaterCress to model runoff into and recharge from check dams.

Assumptions	
Volume of runoff	To evaluate multiple check dams, the model of necessity differentiates between rainfall direct to the water surface area in check dams and runoff from the catchment. This differs from MARVI water balance calculations, where inflow is defined as the sum of direct rainfall to the check-dam water surface plus catchment runoff.
Downstream check-dam volume-to-area relationship	As per the original MARVI study, for downstream check dams, the water surface-area-to-elevation and volume-to-elevation relationships, and hence the volume-to-area relationship, were derived from field surveys with a dumpy level.
Upstream dam volume to area relationship	The capacity and surface area of the 19 upstream check dams were provided by the Watershed Development and Soil Conservation Department, Bhinder, Rajasthan. These were all considerably smaller than the downstream check dams, with an average capacity of ~6 ML and average surface area at full capacity of ~825 m^2 per ML of storage (average depth of 1.4 m). To model the impact of the existing dams the recorded maximum surface area was adopted, and a function—surface area = a + b $\times$ volume $^{0.7}$—was used within the model to estimate the surface area of the storage as it filled and emptied. The factors a and b were set for each storage node such that the maximum volume correlated to the actual maximum surface area. The factor of 0.7 was set to mimic the non-linear relationship between volume and area derived from topographic surveys of the downstream check dams. A similar method was used to model the incrementally increasing capacity of upstream check dams within each catchment, and the maximum surface area of the storage was assumed to increase by 825 m^2 per megalitre of storage increase. This took into account the fact that multiple smaller dams would likely be established rather than a few very large dams, given the physical constraints on storage sites.
Aquifer recharge from all check dams	Aquifer recharge from each check dam is calculated daily by multiplying the surface area of the volume held each day by the infiltration rate. The infiltration rate applied to upstream check dams was assumed to be the same as for the downstream check dams, as defined in Equations (1)–(3). However, the volume of recharge is less, as this is constrained by the smaller surface area of the upstream check dams.

2.4. Modelling Method for the Future Enlarged Check-dam Situation

Using the WaterCress model, it was possible to go beyond an assessment of hydrologic impacts of existing upstream check dams to evaluate the cumulative impacts of upstream check dams of various sizes in order to further explore the trade-offs between recharge from upstream and downstream check dams as upstream check-dam capacity increased. Hence, it also allowed the assessment of the cumulative recharge from all check dams in a catchment as upstream check-dam capacity increased. Thirdly, it allowed a rudimentary evaluation of the effect of upstream check-dam capacity on the proportion of years when the downstream check dam would spill. This is used as a surrogate for impacts on environmental flows downstream of the catchment as a result of the check-dam construction at various scales. While this aspect may not be considered important for the studied catchments, it would be a vital consideration for catchments in many other countries and regions, so is included to demonstrate a first approach to assessing such impacts.

The WaterCress model's depiction of the catchment was simplified so that the stream system was approximated as a single stream channel with a check dam of the current size at the lowest point and check dams of variable but equal capacity on the stream with catchment areas of 1/3 and 2/3 of the whole catchment. Upstream storage capacity was increased by approximately 3 mm over the catchment area to a total of 12 mm in successive simulations, for both catchments, and then to 15 and 24 mm for Hinta. That is, upstream storage capacity was increased by 50 ML increments to 200 ML in the 1705 Ha Dharta catchment and by 25 ML increments to 125 ML and then 200 ML in the 851 Ha Hinta catchment.

The study does not imply that additional check dams are proposed for these catchments, nor identify suitable locations for check dams.

2.5. Method for Economic Evaluation of Optimum Check-Dam Capacity

An economic evaluation of the costs and benefits of the four downstream check dams was undertaken by Dashora et al. (2019) based on check-dam water balances in the years 2014–2016. That work evaluated the unit costs per cubic metre of check-dam capacity in Indian Rupees (INR) by inflating capital costs of construction of check dams from the year of construction to the year 2014 using a discount rate of 8% p.a. based on the long-term average Indian consumer price index. Assuming a 30-year life of a check dam and the same discount rate, the annualised present value of check-dam construction costs (termed AC) was calculated. An average annual maintenance cost was also derived from local records and added to give an annuity to cover the construction and maintenance costs for each downstream check dam. With the average annual recharge determined from each monitored check dam, the mean annual unit cost of recharge (CR) could be determined, and for the four downstream check dams, it was found to be 0.56 INR (2014)/m^3, with Dharta 0.55 and Hinta 0.36 INR (2014)/m^3.

The average annual benefits of use of water for irrigation were determined from the profits for each crop type after taking into account all production costs divided by the annual water use of each crop and weighted according to the proportion of each crop to give a profit per m^3 of irrigation water. In this hydrogeological setting with groundwater extraction taking all accessible water, the proportion of water recharged from check dams that results in additional agricultural production was assumed to be 1.0. Hence, the estimated mean annual unit benefit of check-dam recharge (BR) was determined to be 2.36 INR (2014)/m^3. The benefit–cost ratio, the ratio of BR/CR, had a mean of 4.1 for the downstream check dams.

These values provide the economic parameters to use with new data on capital costs and capacities for the upstream check dams. These were compared with the information from Dashora et al. (2019) [11] for the existing downstream check dams. Hence, the value of water recharged in relation to costs of check dams gave a benefit–cost ratio for each set of costs providing an optimal check-dam capacity for each set of costs for Dharta and Hinta catchments, and thus a sensitivity analysis with respect to check-dam costs.

3. Results

The results are presented first from the water balance calculations derived from farmers' data. Then, we summarise the runoff, recharge, and spill observed in the lower check dams, in the presence of any contemporaneous upstream check dams. This is followed by an evaluation using the WaterCress model to assess existing upstream check dams' impacts on recharge from the Dharta and Hinta check dams. This is followed by a WaterCress modelling assessment of the impact on enlarged upstream check dams with a range of capacities on the recharge from the downstream check dam, the total recharge from all check dams in its subcatchment, and the spill from the downstream check dam for each Dharta and Hinta check dam. Finally, an economic evaluation shows the optimal capacity of check dams in the catchment.

3.1. Runoff from the Study Catchments

By modelling, using the above assumptions (Table 2), the influence of the existing upstream dams was removed (for 2017–2020 in Dharta and Hinta) and gave a "no upstream dam" daily runoff sequence for the four studied catchments for 2014–2020. From this, the annual monsoon-rainfall-to-runoff relationship of each catchment was produced (Figure 2). This suggests the capacity for harvesting water from each catchment for the range of monsoonal rainfall encountered. The figure includes a comparison with estimates from the "Strange Table" developed in 1892 (Mishra et al. 2019) [19] and commonly used in northwestern India.

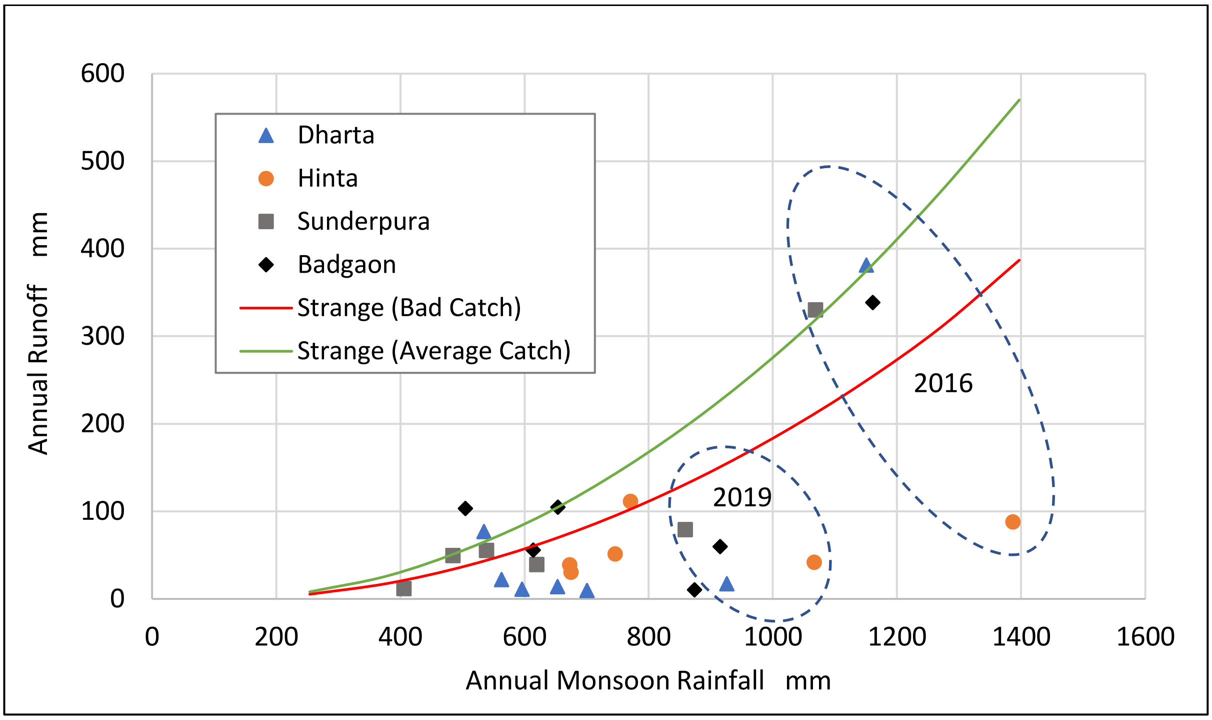


Figure 2. Annual monsoon rainfall/runoff relationships for the four study catchments.

The runoff for the study catchments is generally seen to fall significantly below the Strange "Bad Catchment" curve, no doubt due to pervious soils and relatively low relief. The high runoff grouping of points is for 2016 (>1050 mm), the wettest year, when a spill over each weir occurred for an extended period, and the accuracy of the estimates of a spill is questionable. It is known that some groundwater levels were highest in that wet year, and in places, groundwater discharge to surface water occurred in low-lying parts of the catchments increasing runoff.

Pluviometer data recorded at Hinta between 2018 and 2020 shows that runoff in this catchment is heavily influenced by rainfall intensity rather than total seasonal rainfall. For example, in 2019, the second wettest year (>850 mm), as seen in Figure 2, the intensity, as provided by the Hinta pluviometer, remained low across the entire season. Consequently, Hinta and other check dams received low runoff in 2019 with a magnitude little different from the much drier years.

Over the period 2013–2020, the mean annual rainfall from the five rain gauges in this area is 700 mm with a coefficient of variation of 0.08 (Table 1), giving from the Strange Table an average runoff of 82 mm and 123 mm for "bad" and "average" catchments, respectively. A high frequency of very low runoff years (when runoff is accurately assessed due to a lack of spill) falls below the Strange estimates for a "bad" catchment and suggests that it would not be a reliable method for dam design in this part of India.

3.2. Water Balance for Downstream Check Dams

A water balance method for calculating inflow, recharge, evaporation, and spill in each downstream check dam, based on daily water level and rainfall measurements, is described by Dashora et al. (2018) [1]. The results of applying this for up to 7 years for the four check dams is given in Table 3.

Table 3. Components of the annual water balance for four check dams (2014–2020) (1 ML = 10^3 m^3).

Check Dam	Year	Rainfall mm	Inflow ML	Recharge ML	+Spill ML	Evaporation ML	Recharge /Inflow	Recharge /Capacity	Runoff Coefficient
Badgaon	2014	505	349	113	218	19	0.32	2.86	0.10
	2015	614	189	56	129	5	0.27	1.34	0.06
	2016	1161	1145	143	980	26	0.12	3.4	0.34
	** 2017	525							
	2018	654	355	65	282	8	0.18	1.55	0.10
	2019	915	202	72	106	24	0.36	1.73	0.06
	2020	874	35	30	0	5	0.86	0.71	0.01
Dharta	2014	535	1312	299	954	64	0.23	2.19	0.08
	2015	596	192	157	0	44	0.82	1.13	0.01
	2016	1151	6502	180	6228	94	0.03	1.27	0.38
	2017	653	242	183	0	60	0.76	1.29	0.01
	2018	563	376	263	62	50	0.70	1.85	0.02
	2019	926	297	216	9	72	0.73	1.54	0.02
	2020	701	165	132	0	32	0.80	0.95	0.01
Hinta	2014	771	949	518	358	91	0.55	2.32	0.11
	2015	673	331	286	0	63	0.86	1.28	0.04
	2016	1387	750	388	246	115	0.52	1.48	0.09
	2017	675	261	184	0	76	0.71	0.83	0.03
	2018	746	436	280	71	86	0.64	1.25	0.05
	2019	1067	358	270	0	88	0.75	1.21	0.04
	* 2020	616			0				
Sunderpura	2014	485	54	46	0	8	0.85	0.71	0.05
	2015	406	13	11	0	2	0.85	0.17	0.01
	2016	1069	360	139	177	44	0.39	2.16	0.33
	2017	620	43	32	0	11	0.74	0.48	0.04
	2018	539	60	50	0	11	0.83	0.78	0.06
	2019	859	86	54	0	32	0.63	0.84	0.08
	* 2020	665			0				
All—mean 2014–2020		744	626	172	378	47	0.28	1.44	0.09
All—Mean 2014–2016		779	1012	195	774	48	0.19	1.66	0.13
Badgaon—Median		634	349	72	218	19	0.27	1.73	0.08
Dharta—Median		653	297	183	9	60	0.73	1.29	0.02
Hinta—Median		746	397	283	0	87	0.68	1.27	0.05
Sunderpura—Median		620	57	48	0	11	0.79	0.75	0.05

Notes: * Peak water level did not reach the gaugeboard, preventing water balance calculations in that year. ** Gaps in data prevented the calculation of water balance in that year. + Spill is only crudely estimated, so during a spill, estimates of inflow and the runoff coefficient are also crude.

In the previously reported (Dashora et al. 2019) [11] period of 2014–2016, the mean annual inflow and spill were 60% and 100% higher than for the full 2014–2020 record, because this period included the very wet year of 2016. However, the recharge was only 13% higher, suggesting that the mean annual check-dam recharge is relatively resilient, in comparison with runoff, and averaged about 1.5 times the capacity of the check dams.

These recharge data were vital for calibrating the WaterCress model to predict changes in recharge in downstream check dams due to the establishment of upstream check dams in the Dharta and Hinta catchments. The data show a large inter-annual hydrological variability that superimposes on the development of upstream check-dam capacity, and it suggests that without a calibrated model, it would be extremely difficult to differentiate climatic and anthropogenic effects on the recharge from downstream check dams.

3.3. Existing Upstream Check Dams' Impacts on Recharge from the Downstream Check Dam

This evaluation proceeded through two phases. The first was to establish the reliability of the model to estimate recharge from each downstream check dam. Then, the validated model was applied to the two subcatchments, Dharta and Hinta, over the full period of the record with and without the upstream check dams. This enabled a testable evaluation of the impact of upstream check dams.

3.3.1. Validation of Modelled Recharge in the Downstream Check Dam with the Water Balance Estimate

While the model is faithful to storage in the downstream check dams, there was a need to calibrate the modelled recharge with recharge estimates determined from MARVI water balances that have their own set of assumptions concerning wet-weather infiltration rates (Dashora et al. 2018) [1]. Draw these comparisons required that the upstream check dams be included in the model for the Dharta and Hinta catchments from 2017 to 2020. All other cases were simpler because there were no upstream check dams. Figure 3 compares the modelled and water balance estimates of recharge for each downstream check dam in the four catchments, based on the actual capacity of upstream check dams in the year simulated. It was found that on average, the model accounted for more than 80% of the variance in estimated annual recharge calculated from the check-dam water balance, and it gave total recharge for all check dams within 7% of that estimated by water balance. This was considered a good fit considering the variability among sites and seasons. The two years with the highest recharge and spill in the Hinta catchment, 2014 and 2016, had the largest departures. During periods of spill, the water balance method did not take account of high groundwater levels that could impede recharge rates. Hence, this poorer fit is not considered to impede the use of the model for estimating check-dam recharge.

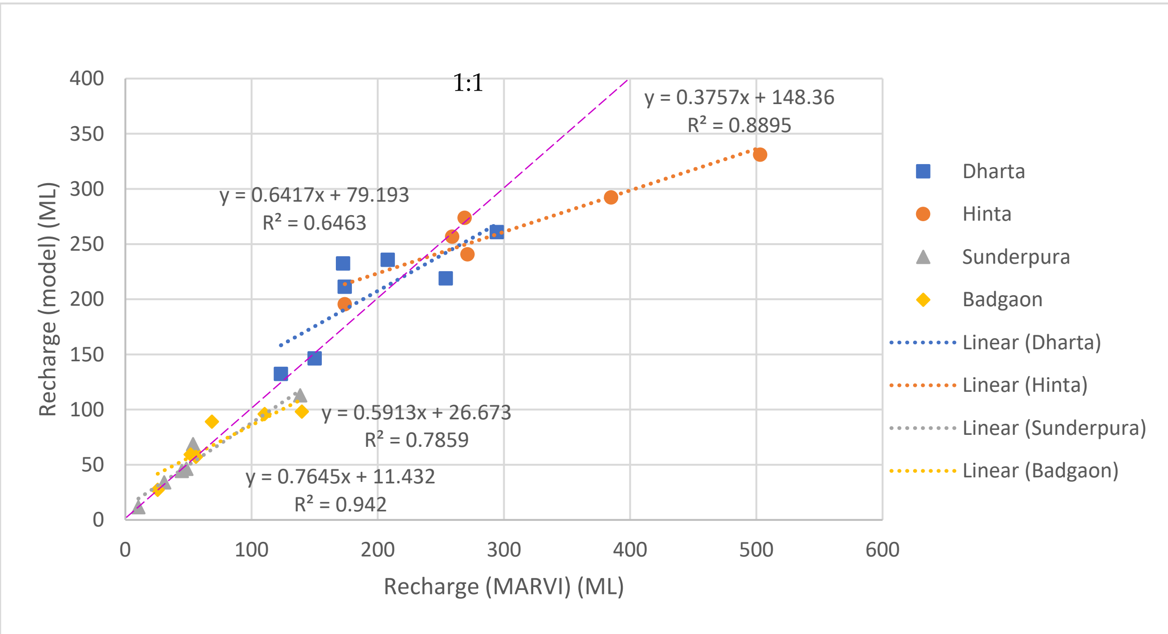


Figure 3. The annual recharge from the WaterCress model estimates compared with recharge calculated from MARVI check-dam water balance measurements (2014–2020).

3.3.2. Upstream Check Dams' Impact on Recharge from the Downstream Check Dam

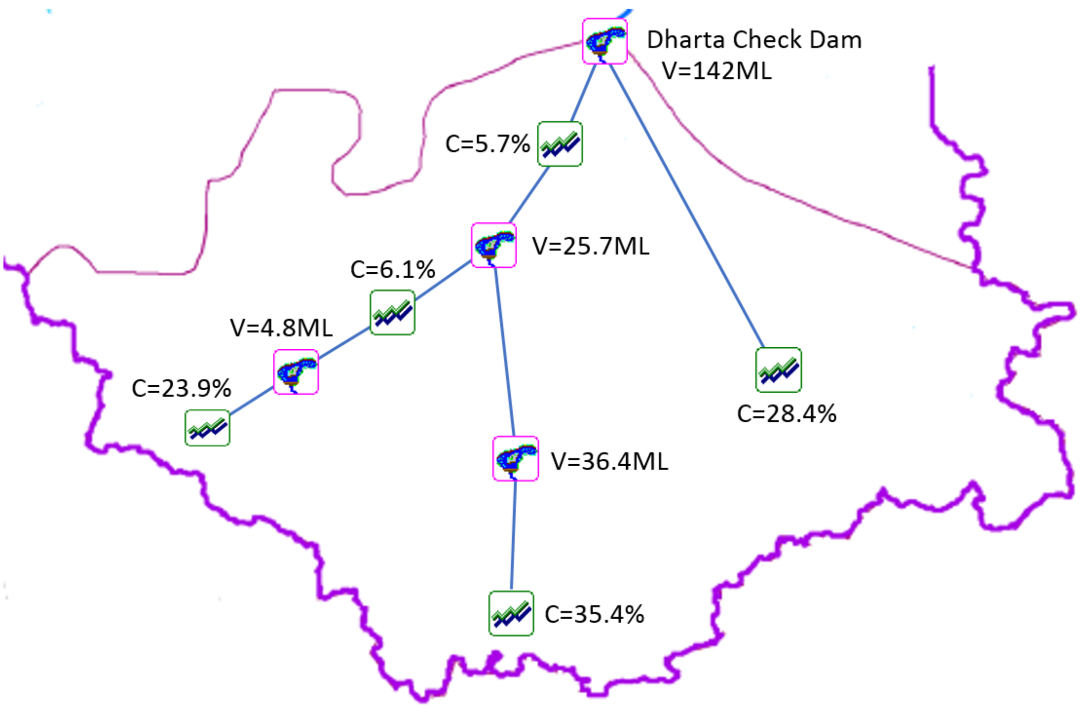
Two studied subcatchments, Dharta and Hinta, had upstream check dams constructed between the 2016 and 2017 monsoon seasons at locations shown in Figure 1 with total capacities shown in Table 4.

Table 4. Capacities of existing check dams in all catchments.

Attribute	Units	Dharta	Hinta	Sunderpura	Badgaon
Catchment area	ha	1705	851	109	338
Check-dam capacity	ML	140	223	64.4	42
Check-dam capacity/Catch. area	mm	8.2	26.2	59	12.4
Capacity of upstream check dams	ML	67	34	0	0
Cumulative check-dam capacity/Catch. area	mm	12.2	30.2	59	12.4
Increase in check-dam capacity	%	48	15	0	0
Catchment median runoff *	ML/year	386	324	45.8	212
Catchment median runoff *	mm	23	38	42	63
Initial capacity/median runoff	%	36	64	140	20

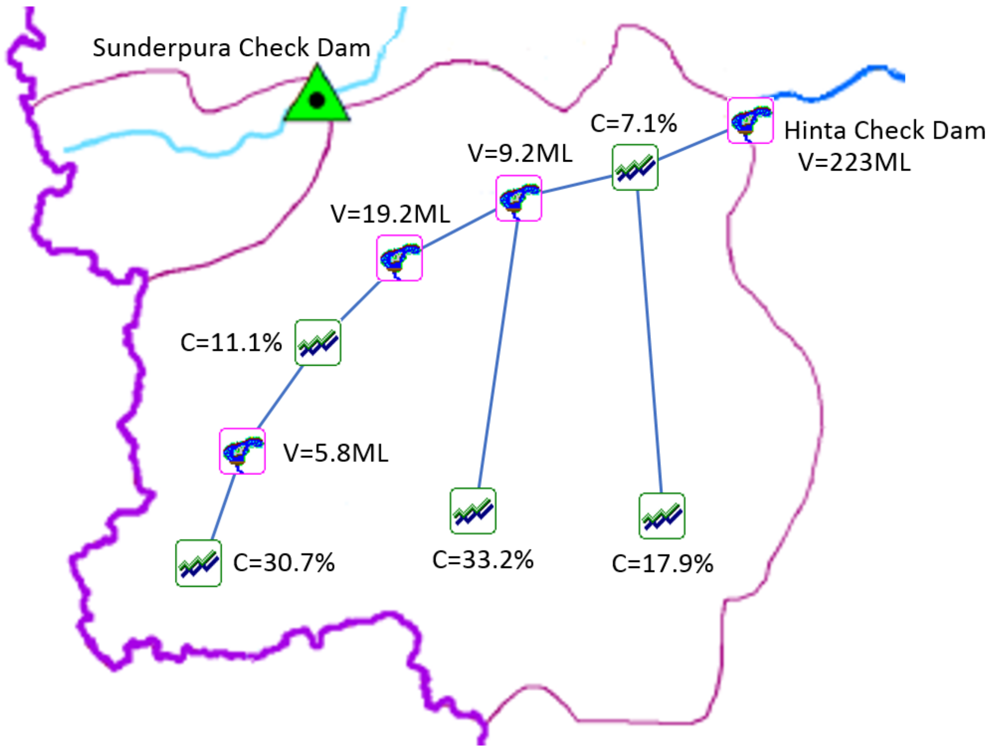
Note: * Modelled median runoff 2014–2020 in the absence of upstream check dams.

To model the influence of the upstream dams, the WaterCress model laid out nodes to simulate the actual dam size and location within each of the study areas. Some consolidation was made where dams were close and essentially influenced the same catchment area. The WaterCress model layout for each catchment is shown in Figure 4. The 12 upstream check dams in Dharta are depicted as 3 consolidated check dams; the 7 upstream check dams in Hinta as 3 check dams; and the sizes, locations, and linkages of all check dams chosen to best represent the actual situation.



(**a**) Dharta catchment

Figure 4. *Cont.*

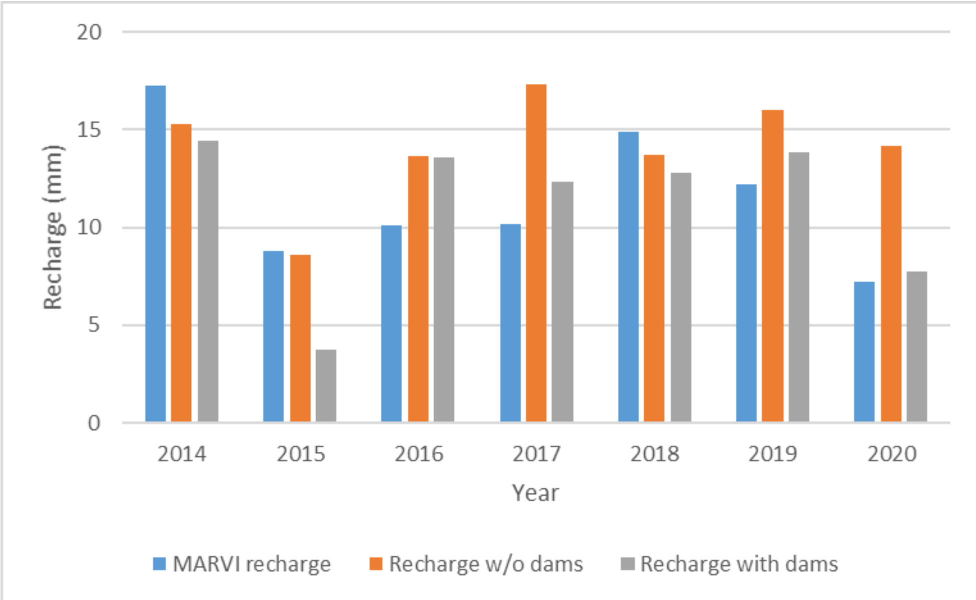


(**b**) Hinta catchment

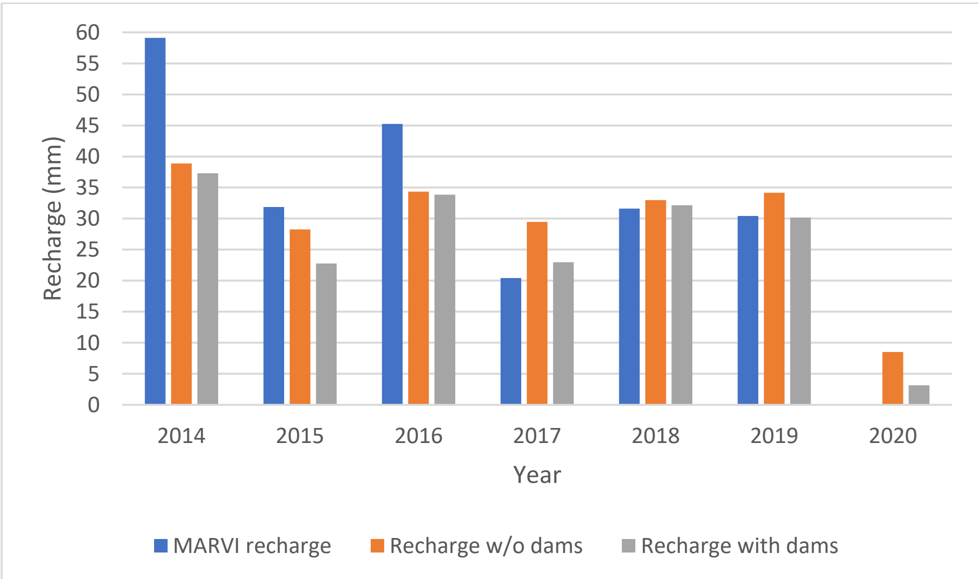
Figure 4. WaterCress schematic representing the existing upstream check dams in the (**a**) Dharta and (**b**) Hinta catchments. Nodes labelled "V" are check dams with volume in ML, and their contributing catchments are labelled "C" showing the percentage of the total catchment area of the downstream check dam.

By using the "no upstream dams" flow sequence as an input to the model, a comparison between recharge with and without existing upstream dams can be made for the entire time sequence of 2014 to 2020 for Dharta and Hinta check dams (Figure 5).

In Figure 5, the year refers to the monsoon. (In some years, check dams contained water and continued to recharge early into the following calendar year.) Note that as the upstream check dams were installed between the 2016 and 2017 monsoons, it is expected that the calculated recharge from the downstream check-dam water balance would better resemble the model without upstream check dams before 2017 and the model with check dams from 2017 onwards. In general, this is true and seen the clearest in years with lower runoff, 2015, 2017 and 2020, when the greatest reduction in the downstream check-dam recharge was predicted by the model for both catchments. In 2016 and 2018, when the predicted decrease in the downstream recharge was marginal, the unexpected model gives at least as good a fit to the estimated recharge from the check-dam water balance in Dharta. The decline in the Dharta check-dam recharge attributed to the upstream dams was 23% for 2017–2020, with 15% predicted for the period of 2014–2016 if the check dams had been installed three years earlier, giving 20% over 2014–2020. The difference between the water balance-estimated (MARVI) recharge at Dharta and the modelled recharge (with the relevant contemporary upstream check-dam capacity) averaged 4.5% of the MARVI calculated recharge. Hence, the decline in the modelled recharge, which was greater than 4 times this difference, suggests that the impacts of upstream check dams are highly significant.



(**a**) Dharta check dam



(**b**) Hinta check dam

Figure 5. Recharge from (**a**) Dharta and (**b**) Hinta check dam by water balance (MARVI) and from the WaterCress model with and without upstream check dams over the whole period of 2014–2020.

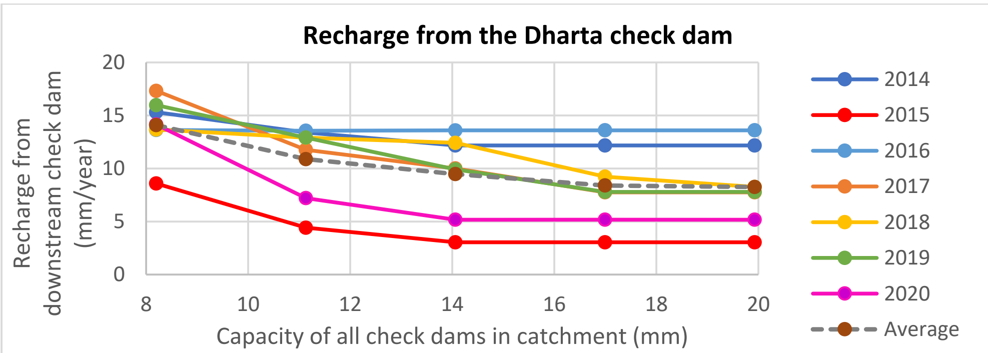
For the Hinta check-dam recharge, excluding the year 2020, with missing data as the water level did not reach the gauge board, the modelled recharge decline due to the upstream check dams was 12% in 2017–2019. For the period 2014–2016, the recharge decline was predicted to have been 7% if the same upstream check dams had been installed three years earlier, giving 10% over 2014–2019. These declines are less than for Dharta, because of the smaller percentage increase in check-dam capacity in Hinta (Table 4). There are large departures between the modelled and the water-balance-calculated recharge estimates for Hinta in the wet years, 2014 and 2016, as shown in Figure 3. Hence, for the 2014–2019 period, the 10% modelled declines are masked by the 15% difference between the modelled recharge and MARVI estimates, for reasons already given. In the drier 2017–2019 period, however, the 12% decline was significant with respect to the 3.4% difference between the model and the MARVI estimates.

For Dharta, the decline in the average water balance-calculated recharge between 2014–2016 and 2017–2020 was 8%. This was less than average decline attributed to upstream check dams. This suggests that the variability of monsoons is of similar magnitude to the effects of the upstream check dams. Interestingly for Hinta, the decline in average water balance-calculated recharge between 2014–2016 and 2017–2019 was 39%, in part due to the water balance method uncertainties in wet years. It also suggests that variations in the magnitude of the monsoon can eclipse the effects of the upstream check dams. The results taken together suggest that without a calibrated model it would be very difficult to quantify the extent of decline in downstream recharge caused by an upstream check dam.

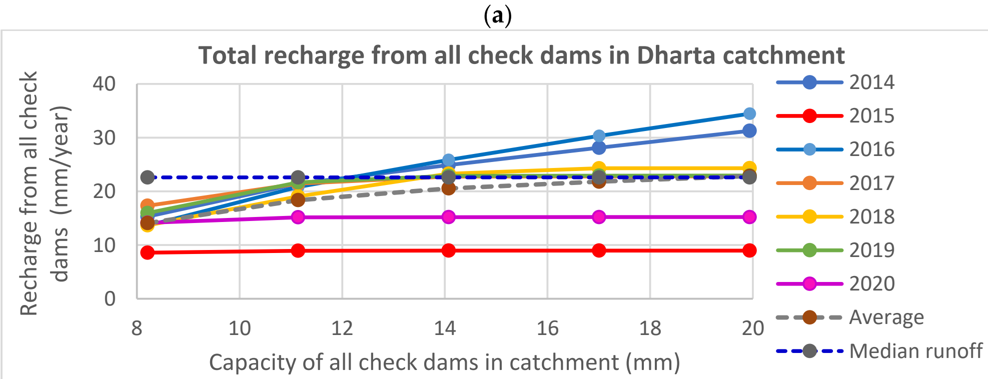
Hence, increasing the check-dam capacity in the catchments by 48% (4.0 mm) to 12.2 mm for Dharta and 15% (4.0 mm) to 30.2 mm for Hinta would have reduced the predicted mean annual recharge at the downstream check dams by 20% and 10%, respectively, if the check dams had been constructed at the outset of hydrologic monitoring. It is noteworthy that in years with lower runoff, such as 2015 and 2020, the predicted decline in the downstream check-dam recharge attributable to the now existing upstream check dams was 56% and 45% in Dharta and 20% and 63% in Hinta. Building more upstream check dams in these catchments would likely further compromise the effectiveness of these check dams in periods when recharge is the most important for local water supply security.

3.4. Impacts of Different Sizes of Future Upstream Check Dams

The results of the simulations for the range of upstream check-dam sizes and for each year of simulation are shown in Figure 6 for Dharta and Figure 7 for Hinta. These give (a) the recharge from the downstream check dam, (b) the total recharge from all check dams in the catchment, and (c) the estimated spill from the downstream check dam.

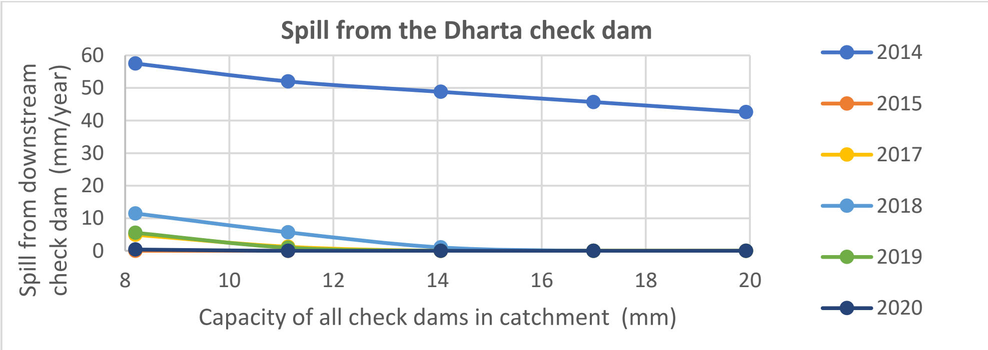


(**a**)



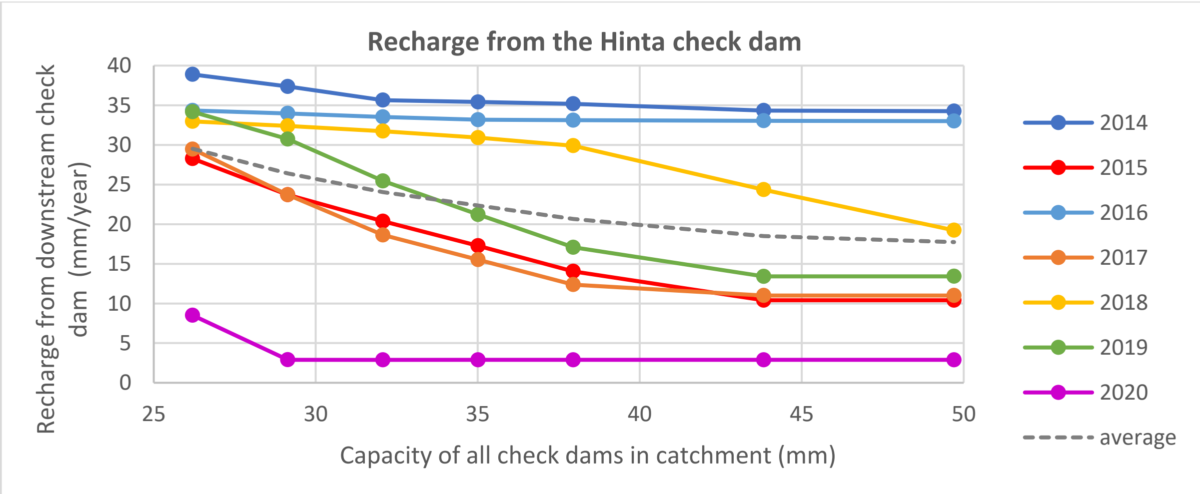
(**b**)

Figure 6. *Cont.*



(**c**)

Figure 6. Predicted impact of hypothetical upstream check-dam development in the Dharta catchment: (**a**) the recharge from the downstream check dam; (**b**) the total recharge from all check dams; and (**c**) the spill from the downstream check. Note that the 2016 estimated spill of 372 mm (reducing to 354 mm) far exceeds other years and is excluded from (**c**). (No spill in 2015, 2017 or 2020.)



(**a**)

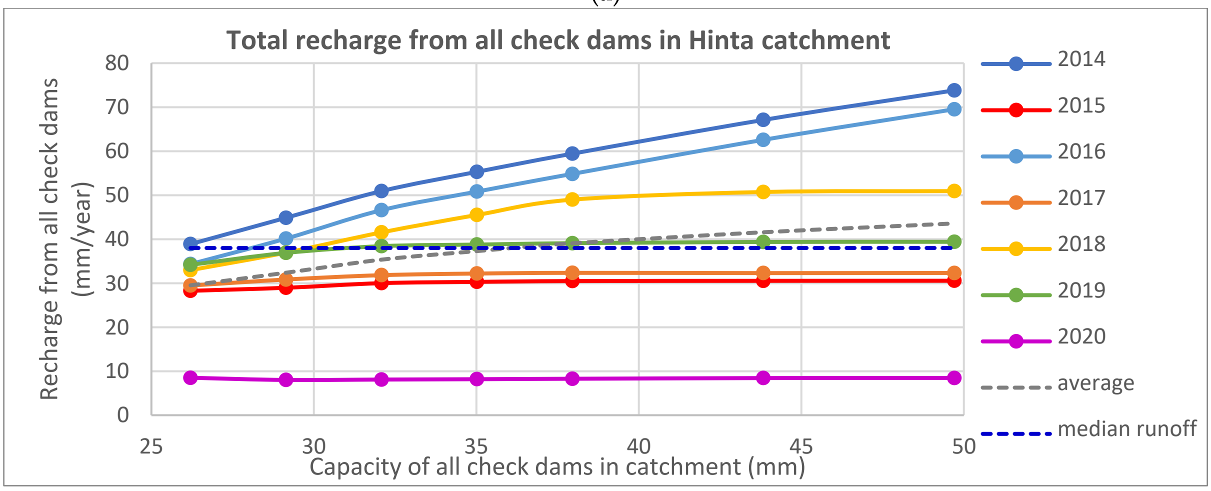


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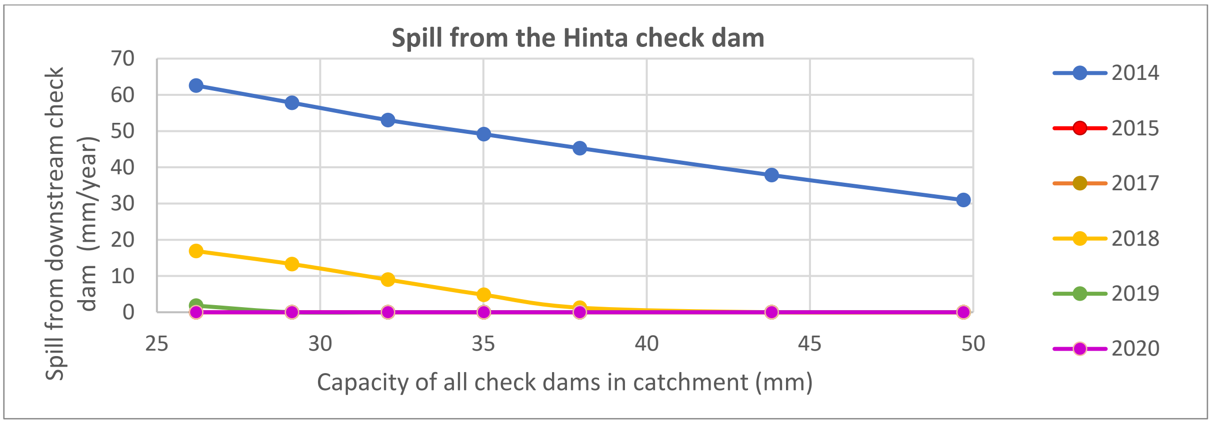
Figure 7. *Cont.*



(**c**)

Figure 7. Predicted impact of the hypothetical upstream check-dam development in the Hinta catchment: (**a**) recharge from the downstream check dam; (**b**) total recharge from all check dams; and (**c**) spill from the downstream check dam. Note that the 2016 estimated spill of 222 mm (reducing to 194 mm) far exceeds other years and is excluded from (**c**). (No spill in 2015, 2017, 2019 or 2020.)

3.4.1. Impact on Recharge from the Downstream Check Dam

Figures 6a and 7a show how the recharge response varies in different years, which can be divided into wet, average, or dry seasons. In the "wetter" years with the highest recharge (2014 and 2016), the recharge from the check dam remains unaffected as upstream dams increase in size. However, in the "drier" years (2015 and 2020 for Dharta and also 2017 for Hinta), the downstream check-dam recharge reduces as the upstream check-dam capacity increases. Downstream check-dam recharge then stabilises at about one-third of the value before upstream check dams were installed, reflecting the proportion of the catchment where flow is unimpeded by those check dams. In the "average" years, there is an intermediate response with a reduced recharge in the downstream check dam but not declining to the same degree, and even with larger upstream check dams in the range evaluated, recharge still exceeded 1/3 the pre-development value. This reflects spill from the smaller upstream check dams contributing inflow to the downstream check dam.

3.4.2. Impact on Total Recharge from All Check Dams

Figures 6b and 7b show for "wetter" years significant additional total recharge can be achieved by adding more upstream check dams. In "drier" years, upstream check dams offer little or no additional total recharge from check dams. However, for "average" rainfall/runoff years (2017, 2018, and in Dharta also 2019), the total check-dam recharge reaches an upper limit following the construction of 100 ML (6 mm) of upstream dams with a total storage capacity of 14 mm (expressed as mm detention over the whole catchment area). This corresponds to the observed maximum runoff that occurred in years with no spill from the Dharta catchment. For Hinta, exactly the same patterns were applied with the exception that the "average" years (2018 and 2019) reached their maximum values with a total storage capacity of 41 and 28 mm, respectively, again corresponding to the maximum values of runoff observed without a spill.

Dam construction in the Dharta catchment was able to provide additional benefit as the initial check-dam capacity (8.2 mm) is relatively small compared to the median runoff from the catchment (23 mm, Table 4). In Hinta, a more developed catchment, with the initial check-dam capacity of 26.2 mm, and a median runoff of 38 mm, it would be expected that increasing the check-dam capacity would have a smaller impact on total recharge.

3.4.3. Impact on Spill from the Downstream Check Dam

In the absence of upstream check dams, spills from the Dharta check dam (Figure 6c) occurred in six of the seven years, with only the driest year, 2015, having no spill. In the absence of a requirement to maintain the spill for environmental flows or to satisfy equitable sharing of water between upstream and downstream communities, this suggests a potential for additional check dams in the catchment. If upstream check dams were built and their capacity reached 150 ML (an additional 15 mm, totalling 23 mm), only the two wettest years in seven would have resulted in spill.

In contrast, the smaller Hinta catchment (Figure 7c) had a larger downstream check dam, and little or no spill occurred in four of the seven years simulated with no check dams upstream. Hence, in these years, there would be no additional recharge benefit if upstream check dams were built. Beyond an additional 150 ML capacity (an additional 15 mm, totalling 41 mm), only the two wettest years in seven would have resulted in spill.

3.5. Economic Evaluation of Optimum Check-Dam Capacity

The 19 upstream check dams were all constructed in 2017, and their capacity ranged from 1.1 to 25.2 ML and averaged ~6 ML. Accounting for the effect of scale on cost, approximated from the downstream check dams that ranged in size from 42 to 223 ML, and for 3 years of inflation at the same 8% p.a., upstream check-dam costs averaged more than 4 times the costs anticipated by interpolating costs for the downstream check dams (Figure 8). Two reasons are hypothesised: firstly, the scale-efficiency impact on cost is more than projected, and secondly, the most prospective sites are established first so that subsequent sites are less efficient for constructing check dams.

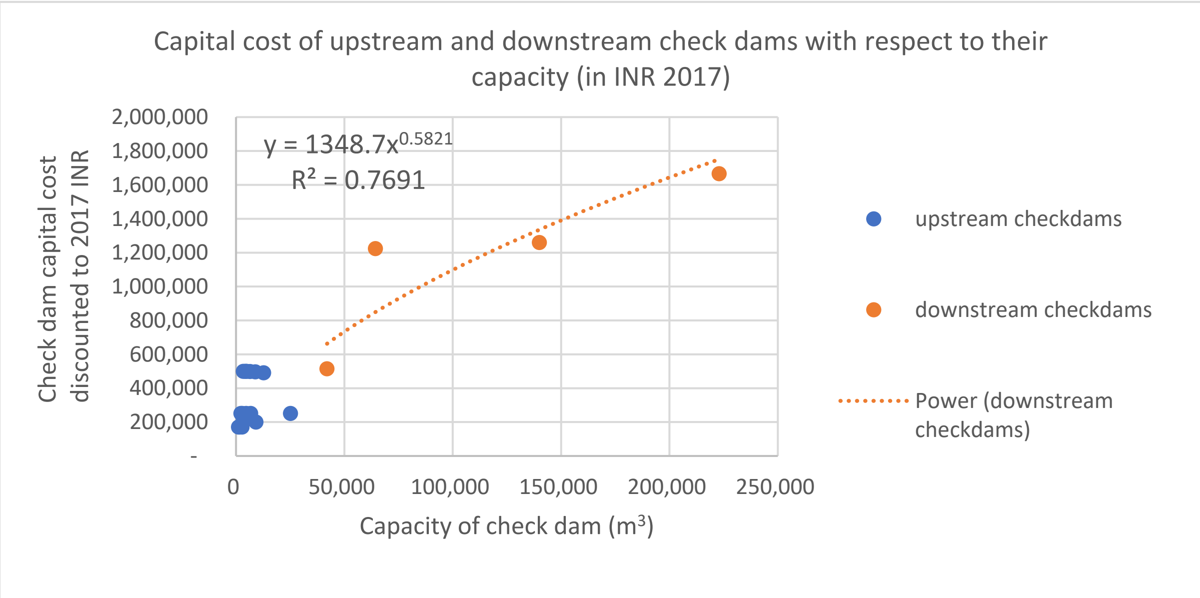


Figure 8. Capital costs of upstream and downstream check dams were compared discounted to 2017, the year of construction of upstream check dams. Costs are in Indian Rupees (INR).

As the benefit–cost ratio is independent of the year chosen for present value analysis when only mean annualised costs are used, the costs of upstream check dams and scaled mean annual maintenance costs were discounted to 2014 values in INR in order to simplify calculations. The analysis was undertaken in two phases.

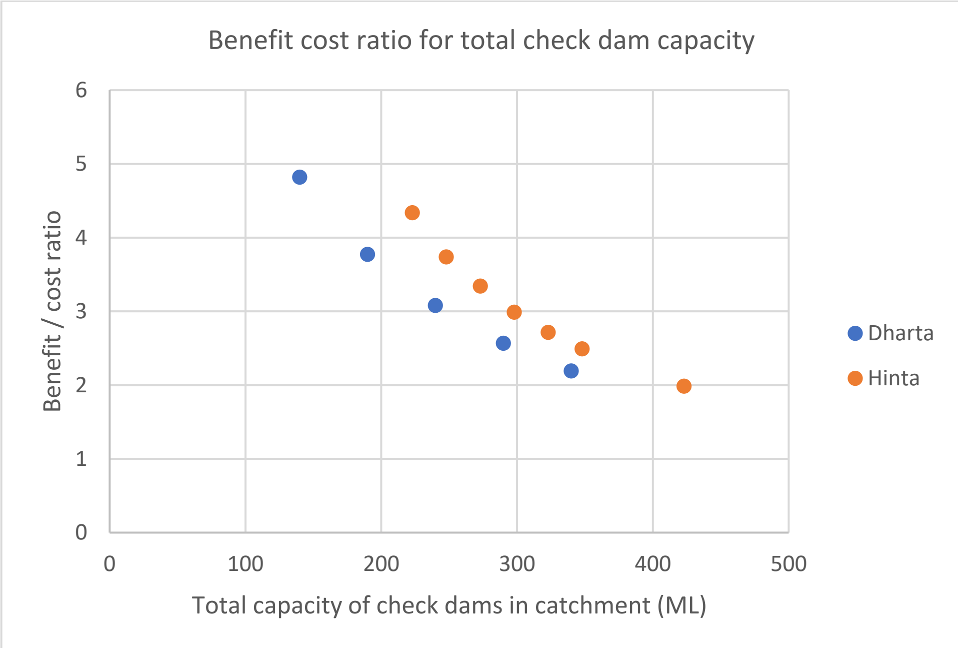
In the first phase, the benefit–cost ratio was determined for the total check-dam recharge for the Dharta and Hinta catchments, treating the investments as packages of different scales. It was assumed that the costs of the upstream check-dam capacity followed the pattern of the downstream check dams.

Recharge estimates for all check dams in a catchment (Figures 6b and 7b) could be used with the parameters shown in Table 5 to determine the benefit–cost ratio of each check-dam expansion option. This allowed the apparent optimum total capacity of recharge structures to be determined for the Dharta and Hinta subcatchments (Figure 8).

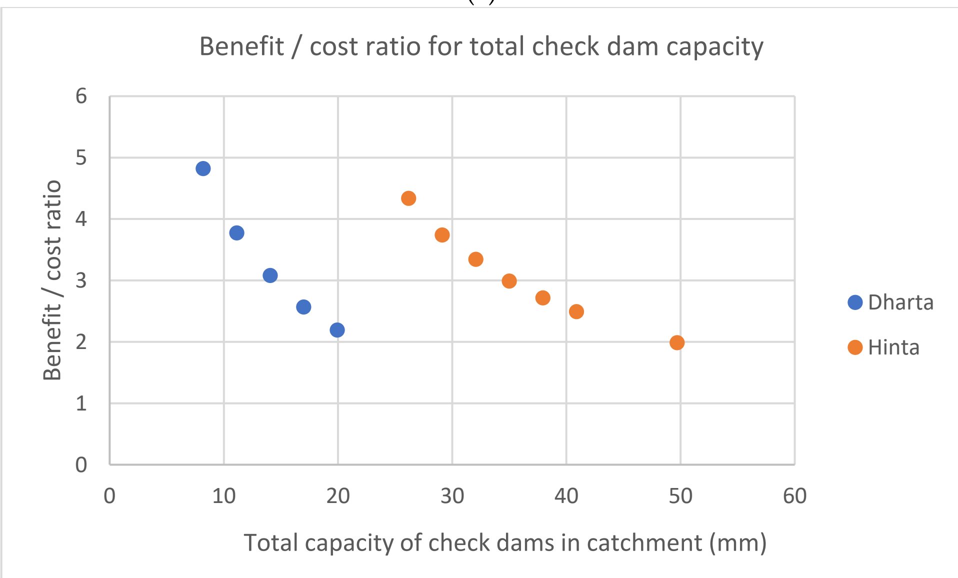
Table 5. Economic valuation of optimum total check-dam capacity based on statistics available for four downstream check dams in this catchment (Dashora et al. 2019) and results of the WaterCress modelling reported above.

Attribute	Units	Value	Reference
Discount rate (r) (% per annum)	% p.a.	8.0	Dashora et al. (2019) [11] Equation (2)
Operating life (with assumed level of maintenance costs) (L)	years	30	Dashora et al. (2019) [11] Equation (2)
Proportion of check-dam recharge that results in additional agricultural production (g)	-	1.0	Dashora et al. (2019) [11] Equation (8)
Value of recharged water (BR)	INR (2014)/m^3	2.36	Dashora et al. (2019) [11] Table 9
Annualised costs for capital and maintenance costs of 4 downstream check dams (ACM)	INR (2014)/year	437,000	Dashora et al. (2019) [11] Equation (4) Table 8
Mean annual recharge 2014–2016 for 4 downstream check dams (MR)	m^3/year	779,000	Dashora et al. (2019) [11] Equation (5) Table 8
Average unit cost of annual recharge from 4 downstream check dams (2014–2016) (CR)	INR (2014)/m^3 recharge	0.56	Dashora et al. (2019) [11] Table 8 Dharta 0.55 Hinta 0.36
Capacity of 4 downstream check dams (cap)	m^3	469,400	Dashora et al. (2019) [11] Table 6
Present value of capital costs/m^3 capacity (average of 4 downstream check dams)	(INR/m^3 cap) (2014)	7.9	Dashora et al. (2019) [11] Table 6
Annualised costs for capital and maintenance costs of 4 downstream check dams/m^3 capacity (ACM/cap)	INR (2014)/m^3 capacity	0.93	Dashora et al. (2019) [11] Tables 6 and 8
ACM for 50 ML increment in capacity of upstream check dams (ACM) based on scaling downstream check-dam costs	INR (2014)/year	80,000	Dashora et al. (2019) [11] Table 8, Regression: $y = 972\ cap^{0.408}$ ($R^2 = 0.781$) Includes mean annual maintenance cost (MAM)/cap of 0.23 INR(2014)/year/m^3
ACM/cap for 50 ML increment in capacity	INR (2014)/m^3 capacity	1.6	Using capacity scaled costs from downstream check dams (i.e., smaller scale increases costs by 1.6/0.93)
ACM/cap for 50 ML increment in capacity based on upstream dam construction costs (from Govt. Department)	INR (2014)/year	340,000	2017 upstream cap costs discounted to 2014 and using the same MAM costs per unit capacity. (This is 4.26 times greater than costs based on the first (downstream) check dams.

Figure 9 shows that when check-dam investments are aggregated, the present value of benefits exceeds the present value of costs for all scenarios in the case where the cost per unit capacity for upstream check dams falls on the scale-efficiency cost curve defined by the downstream check dams. However, the BCR decreases from more than 4 for the case of downstream check dams alone to around 2 when the total upstream check-dam capacity approximates the capacity of the downstream check dam. It is evident that the high benefit–cost ratio of the large downstream check dam in each subcatchment overshadows the lower benefit–cost ratios of subsequent expansions in the check-dam capacity upstream. Normally, the decision to augment the check-dam capacity within a catchment would constitute a sequence of decisions, and the benefits and costs of each new check dam would be evaluated independently. This effect of incremental investment in upstream check-dam capacity is shown more clearly in Figure 10.



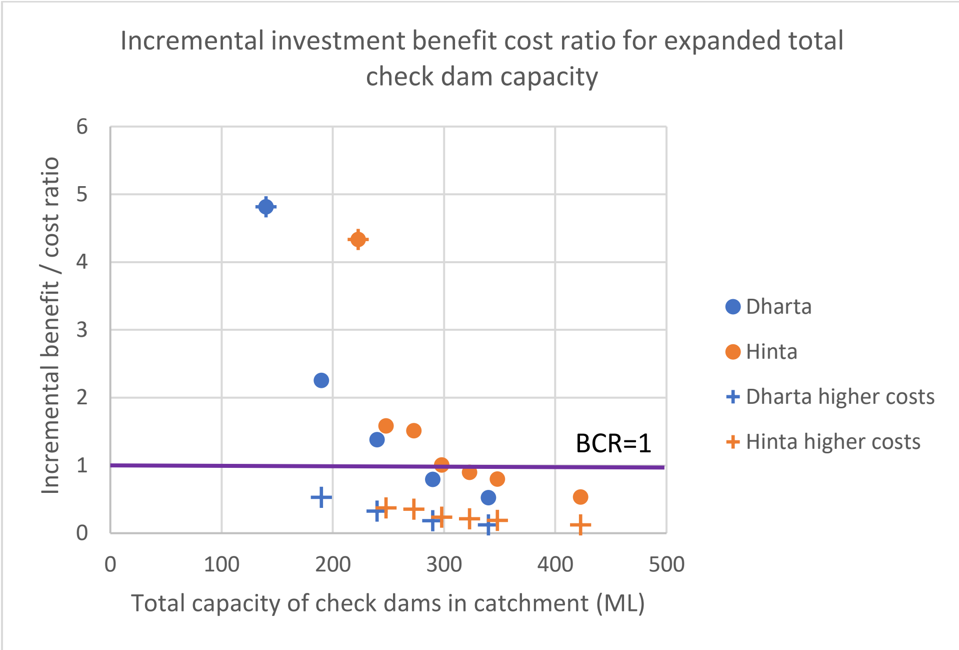
(**a**)



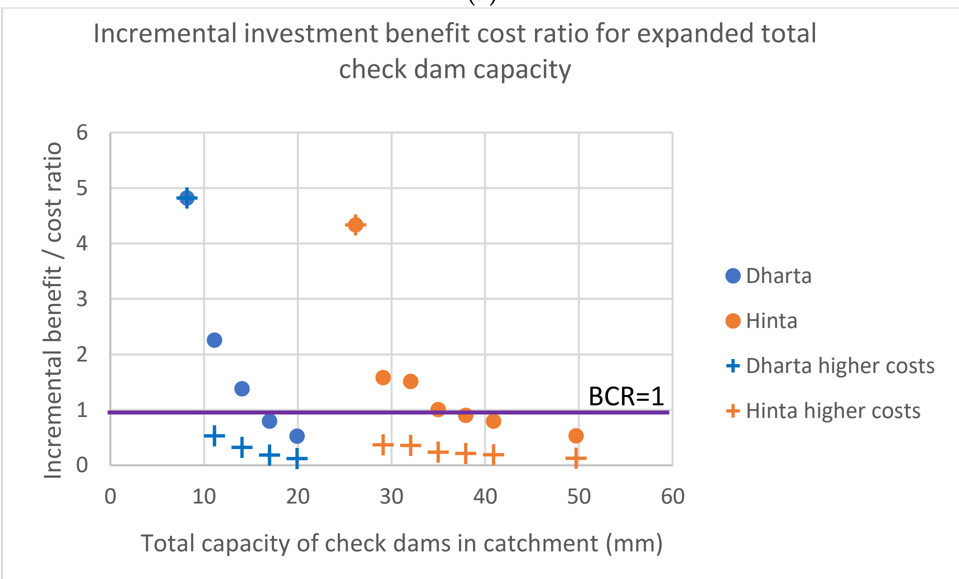
(**b**)

Figure 9. Expected benefit–cost ratio of consortia of check dams in Dharta and Hinta catchments for a range of aggregate capacity, expressed as (**a**) megalitres and (**b**) millimetres over the whole catchment area.

Figure 10 shows that the benefit–cost ratio (BCR) declines quickly with each new increment and the optimal total check-dam capacity is that immediately before the next incremental BCR drops below 1. In the case of similar trajectory of dam costs for a given capacity as for downstream check dams, the optimum total capacity of check dams in Dharta is 240 ML (14 mm) and in Hinta 273 ML (32 mm). These are 61% and 84% of the modelled median annual runoff of 23 mm and 38 mm in Dharta and Hinta, respectively (Table 4).



(**a**)



(**b**)

Figure 10. Expected benefit–cost ratio of incremental investments in check dams in the Dharta and Hinta catchments for a range of aggregate capacity, expressed as (**a**) megalitres and (**b**) millimetres over the whole catchment area. Graphs show cases where upstream check-dam costs have the same discounted costs as downstream check dams and also when the unit capacity costs are higher by a factor of 4.26, matching the discounted actual costs reported for these catchments.

However, taking into account the increase in unit costs of dams by a factor of 4.26, based on costs of actual upstream check dams built in 2017 (discounted to a consistent 2014 INR value), and retaining the same mean annual maintenance cost (MAM) per m^3 capacity of check dams (0.23 INR(2014)/year/m^3) (Table 5), the BCR declines faster with each increment in capacity. The optimum total capacity of check dams in Dharta is 140 ML (8 mm) and in Hinta is 223 ML (26 mm). That is, it is uneconomic to expand check-dam capacity in Dharta and Hinta considering the less efficient check-dam sites actually available as revealed by the government's observed actual costs of installing upstream check dams in 2017. This is in spite of predictions based on historical costs that an additional 100 ML in

Dharta and 50 ML in Hinta would have been optimal, which is about 50% larger than the upstream check-dam capacity installed in both catchments in 2017.

Hence, the optimal level of investment in check dams depends on the hydrology of the catchment as well as the costs of new check dams at the state of development of the catchment-detention capacity. As the preferred sites for check dams become utilised, the remaining sites are likely to be less economic, so the results for the higher cost scenarios are likely to be a more reliable predictor of optimal development of check dams in catchments than the stationary cost scenarios.

4. Discussion

For Dharta and Hinta the optimum total check-dam storage capacity is 61% and 84% of the median annual runoff, respectively, if relative costs of new check dams do not increase. With elevated costs of construction as observed in 2017, even the first incremental expansion beyond 27% and 53% of median annual runoff, respectively, is not on average economically attractive. On this sparse basis, the order of 30 to 50% of median annual runoff is a plausible guess for target-detention capacity in a catchment, which may approximate optimal investment in recharge enhancement.

However, the differences in these results between adjacent subcatchments of different sizes and compositions suggest that simple rules of thumb are unlikely to be transferable even to nearby catchments. Since the unreliability of the Strange Table for predicting runoff coefficient over a monsoon has already been shown, this suggests that effort is warranted to monitor existing dams and check dams to determine likely runoff from catchments and hence the ability to capture additional runoff for groundwater recharge. Due to the variability in the monsoon rainfall and runoff from year to year, several years of records will be needed to establish reliable values for median annual flows.

The construction of upstream check dams in Dharta and Hinta subcatchments in 2017 was coincidentally found to be at about two-thirds of the optimal investment in additional storage capacity for recharge enhancement, assuming the stationarity of the check dams' construction costs, but larger than optimum accounting for less efficient remaining sites. These actual upstream check dams increased the total recharge in the catchment, but they also had the effect of reducing the recharge from the downstream check dam by 20% for Dharta and 10% for Hinta.

Additional check dams were found by modelling to reduce the spill volume and frequency from the downstream check dam. Spill volumes calculated by the check-dam water balance were unreliable due to only daily monitoring of check-dam levels, so the analysis has focused on the spill frequency changes as a result of additional check dams. The model showed that the frequency of spills from the Dharta check dam decreased from 6 in 7 years to 3 in 7 years when 100 ML upstream check dams were built. For Hinta, the construction of 50 ML upstream check dams reduced spill frequency from 4 in 7 years to 3 in 7 years. The impacts were most noticeable in years with low to moderate runoff.

In jurisdictions where there are requirements to sustain flows in a stream for stream ecosystem protection or to meet legal entitlements of downstream users, low-flow bypass may be incorporated into check-dam design to ensure that such requirements are met. The WaterCress model, and no doubt other hydrologic models, can be used to assist in the design of check dams for this purpose. Criteria for environmental flows, such as timing, duration, minimum flow rate, the proportion of flow that may be retained, temperature, and other water-quality parameters, specific to the relevant environmental and legal conditions, influence the check-dam design and may constrain the potential to recharge water from check dams. As this was not a requirement in the current study in Udaipur, the impacts of environmental flow constraints on recharge were not explored.

The farmers (Bhujal Jankars) who undertook the daily measurements performed very reliably, as illustrated by the accuracy of their water level measurements (Dashora et al. (2018, Figure 6) [1]). However, from this study, there are several improvements to the design of monitoring systems that would give more complete data and hence more definitive predictions. Firstly, if several gauge boards had been placed in each check dam to enable water level records over the full depth range, then water balances could have been be obtained in drier years and at the start and end of all monsoon seasons. If water level loggers had been installed in check dams, then much more reliable estimates of spill could have been obtained, and hence inflows and runoff coefficients would be better defined. Thirdly, there would be value in having at least one observation well immediately adjacent to each monitored check dam in order to enable the assessment of hydraulic connection between the check dam and the underlying aquifer and to provide a more rigorous way of assessing wet weather infiltration rates in wet years.

This paper has so far not discussed the impacts of the recharge enhancement on groundwater quality. As the source water is unchanged and the mechanism of infiltration through the streambed is identical to the natural recharge, no adverse impacts would be expected on groundwater quality (Dillon et al. 2014) [20]. Multiple check dams could potentially lower salinity and fluoride concentrations by inference from a study in the same catchment where groundwater quality variations in direct well recharge structures were evaluated by Soni et al. (2020) [21].

5. Conclusions

This study has presented the first evidence known to authors of the cumulative impact of check dams in catchments. In particular, the study revealed the decline in the effectiveness of downstream check dams for groundwater recharge due to check dams built upstream. It also revealed the most economic density of capacity of check dams in catchments in relation to total check dam recharge. The effects of upstream check dams on downstream check dam spill frequency were also shown. The optimal total check-dam storage capacity for adjacent catchments of different sizes was predicted to be 61% to 84% of the median annual flow (modelled with upstream check dams excluded). This assumed that the cost per unit capacity for new check dams was the same as for those existing in 2016, which had capacities of 27% and 53% of the modelled median annual flow. However, the actual unit costs of new check dams built in 2017 were found to be more than four times higher, possibly because more cost-efficient (larger) sites had already been occupied. Consequently, the expansion of check-dam capacity beyond 2016 capacities was found to be economically unjustified at these higher costs.

The WaterCress modelling using field data indicated that downstream impacts of new check dams in drier years can considerably reduce the recharge and frequency of spills from downstream check dams. The combined recharge from all existing and new check dams in the catchment increased only marginally in dry years, but substantially in wet years. There was declining incremental economic benefit from additional new check dams in the catchment, so extra check dams may not necessarily mean more recharge.

The study showed that monitoring check dams, rainfall, and groundwater levels is key to deciding whether additional check dams are economically beneficial and have good value for government funds. The work reported in this study is a first step towards developing policy and planning guidance to maximise the benefit of investment in check dams and other recharge structures in watershed development programs at the catchment scale. In jurisdictions where environmental flows are specified, check-dam designs that allow low-flow bypass of water would be useful, and the WaterCress model used in this study could be updated to simulate these and evaluate the achievement of target flows.

This study concludes that to make use of these findings elsewhere to expand and improve investment in check-dam programs, the main knowledge gap is the absence of hydrologic data, namely rainfall, check-dam water level, and groundwater level close to check dams. Informed farmers collecting data as part of a watershed development program, such as MARVI, using methods described by Dashora et al. (2018) [1] to give results such as those presented in this paper, would empower other communities (through citizen science) and give a low-cost starting point to inform future investment in check dams through government programs. The annual costs of such monitoring were found to be less than 1%

of construction costs of check dams and gave a reliable estimate of recharge enhancement, and they can help to identify when the desilting of a check dam is needed. Given that benefit–cost ratios exceeding 4 have been found in this study but are highly variable at different scales, investment in data collection as part of watershed development programs will be critical to maximising the value and impact of future check dams.

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