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Benefits, equity, and sustainability of community rainwater harvesting structures: An assessment based on farm scale social survey

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Rainwater harvesting systems (RWHs) are implemented globally to bridge the frequent water supply-demand gaps. This study explores, through farmer household surveys (n = 492), how farmers perceived the benefits of RWHs, the equitability of benefits, and the role of contextual and psychological factors towards the behaviour of maintaining such systems. The study is carried out in a semi-arid catchment in the Indian state of Gujarat where RWHs, in the form of Check dams (CDs), have been implemented extensively. Results show that the benefits of CDs are perceived in good rainfall years through enhanced availability of water for expanding crops and irrigated areas. Farmers reported limited benefits of CDs in dry years. This is because of limited runoff and no carryover of stored groundwater, due to underlying shallow hard rock aquifer with little primary porosity, from wet years to dry years. Overall, ~ 40%–50% of sampled farmers reported no benefits from CDs and the benefits decreased with distance. This reflects a spatially inequitable distribution of benefits skewed towards the farmers nearest to the CDs. The sustainability of CDs is a challenge with already ~40% of CDs reportedly not working and 72.8% of farmers reported doing no maintenance activity. This is because 91.2% of farmers reported playing no role in its construction. The results show contextual (participation during construction, economic indicators) and sociopsychological factors (attention to CD condition, maintenance effort) significantly affect the behaviour towards maintaining the CDs. This highlights the need to complement RWHs with wider drought management and water demand management interventions to achieve drought resilience, and adherence to project exit protocols to secure the sustainability of investments.

KEYWORDS

rainwater harvesting structures, check dams, benefits, sustainability, equity, RANAS, groundwater

1 Introduction

Agriculture accounts for 70% of total freshwater withdrawals globally, going up-to 90% in developing countries (FAO, 2022). As a result, it is highly vulnerable to water shortages resulting from unpredictable and unreliable availability of water. This is particularly a concern in arid and semi-arid regions that face high variability in the availability of water, which is characterized by short rainfall seasons, frequent dry periods, and droughts (Falkenmark et al., 1989; Ragab and Prudhomme, 2002). The climate change impacts manifested through increases in water extremes are already intensifying the existing risks (United Nations, 2019; IPCC 2022) posing concerns for water and food security in large parts of the world.

As an adaptation measure and to bridge the frequent supply-demand gaps in semi-arid regions, *ex-situ* rainwater harvesting systems (RWHs) that collect rainwater in surface reservoirs or recharge groundwater (e.g., check dams, farm ponds, tanks, percolation tanks), have been one of the key interventions in agricultural areas (Alam and Pavelic, 2020; Garg et al., 2020; Sikka et al., 2022). The reported benefits from such RWHs include increased water availability, increased crop yields, increased groundwater storages, diversification of water uses and mitigation of droughts (Glendenning et al., 2012; Bouma et al., 2016; Singh et al., 2018; Garg et al., 2020; Patel et al., 2020; Parker et al., 2022).

In India, with large parts under arid and semi-arid climate, government and non-government organizations have also heavily invested in building RWHs under different water management programs (Joshi et al., 2008; Sikka et al., 2022). One such example is of Gujarat, a state in western India (Figure 1A) where it has invested heavily in RWHs, largely through the construction of check dams (small structures with low storage built across smaller streams) (Verma and Shah, 2019; Patel et al., 2020). In total, more than 90,000 check dams (hereafter referred as CDs) have been constructed with the financial support from government and non-government organizations (NWRWS, 2018).

Despite multiple studies that have documented positive impacts of CDs on groundwater and agriculture in the region (Shah et al., 2009; Jain, 2012; Patel et al., 2020), disagreements remain on the extent to which the positive impacts can be attributed to CDs (Kumar et al., 2008; Alam et al., 2022b). Additionally, concerns have also been raised that these RWHs may not always be effective or beneficial in arid and semi-arid regions (Kumar et al., 2008; Glendenning & Vervoort, 2011), may lead to inequitable benefits (Deora and Nanore, 2019; Alam et al., 2022a) and are not sustained due to the neglect of maintenance and lack of clear ownership (Sharma, 2007; Venot et al., 2012; Singh, 2018).

The concerns about the efficacy of benefits arise because semi-arid areas have low rainfall with high interannual variability and thus the runoff available for storage or recharge is very limited and often negligible in dry years (Enfors et al., 2008; Kumar et al., 2008; Glendenning & Vervoort, 2011; Oglivie et al., 2019; Alam et al., 2022b). Further, the benefits of RWHs may not be equitably distributed. The farmers nearby the streams where RWHs are built (Deora and Nanore, 2019; Shah et al., 2021), and rich and influential farmers with the capacity to invest in irrigation and agronomy measures benefit more from increased availability of water (Calder et al., 2008; Bouma et al., 2011; Alam et al., 2022a). The sustainability concerns arise from little or no maintenance of such structures once the project is over, representing the build-neglect-rebuild syndrome (Sharma, 2007; Venot et al., 2012; Singh, 2018). Additionally, there are concerns that increased perception of supply from RWHs may have led to more demand in the region, offsetting the benefits of increased supply (Alam et al., 2022b).

Most of the studies assessing the impacts of CDs in the region (Shah et al., 2009; Jain, 2012; Patel et al., 2020; Alam et al., 2022b) have been technical in nature either at a larger spatial scale (regional or catchment) (Shah et al., 2009; Patel et al., 2020; Alam et al., 2022b) or focus on standalone CD structures (Patel et al., 2002; Sharda et al., 2006; Mozzi et al., 2021). These studies do not shed light on how farmers, the ultimate beneficiaries of CDs, perceive the impacts of CDs and benefit from it. For example, Shah (2001) estimated that CDs benefited only 15%–16% of households in the villages of the region where CDs were constructed. Additionally, these studies do not account for the equitability of impacts and the sustainability of the investments.

Therefore this study employs farmer's surveys to assess the benefits, equity, and sustainability of investments made in CDs to complement the existing studies and fill the abovementioned research gaps. The adoption of interventions, equated here with farmers' behavior towards the maintenance of RWHs, critical for the sustainability of corresponding investments, is influenced by range of socio-economic, psychological, perceptual, and cultural factors (Kaufmann et al., 2009; Daniel et al., 2020). The RANAS (i.e., R-risk, A-attitude, N-norm, A-ability, and S-self-regulation) behaviour model has been used to consider such diverse set of factors on the behaviour of adoption (Mosler, 2012). The model was originally developed for the WaSH sector, which assumes that multiple sociopsychological factors (i.e., risk, attitude, norm, ability, and self-regulation) impact behavioral outcomes (i.e., behavior, intention, use, and habit). The model has been used previously to understand farmer behavior with respect to irrigation practices (Hatch et al., 2022), willingness to conserve groundwater (Klessens et al., 2022) and household water treatment behavior (Daniel et al., 2020, 21; Stockler and Mosler, 2015).

This study employs the RANAS model and descriptive analysis of a farmers survey to answer two research questions: 1) How do farmers perceive the benefits of RWHs and equitability of benefits? and 2) what are the contextual and socio-psychological factors that influence the sustainability of RWHs through the lens of farmers' behavior towards the

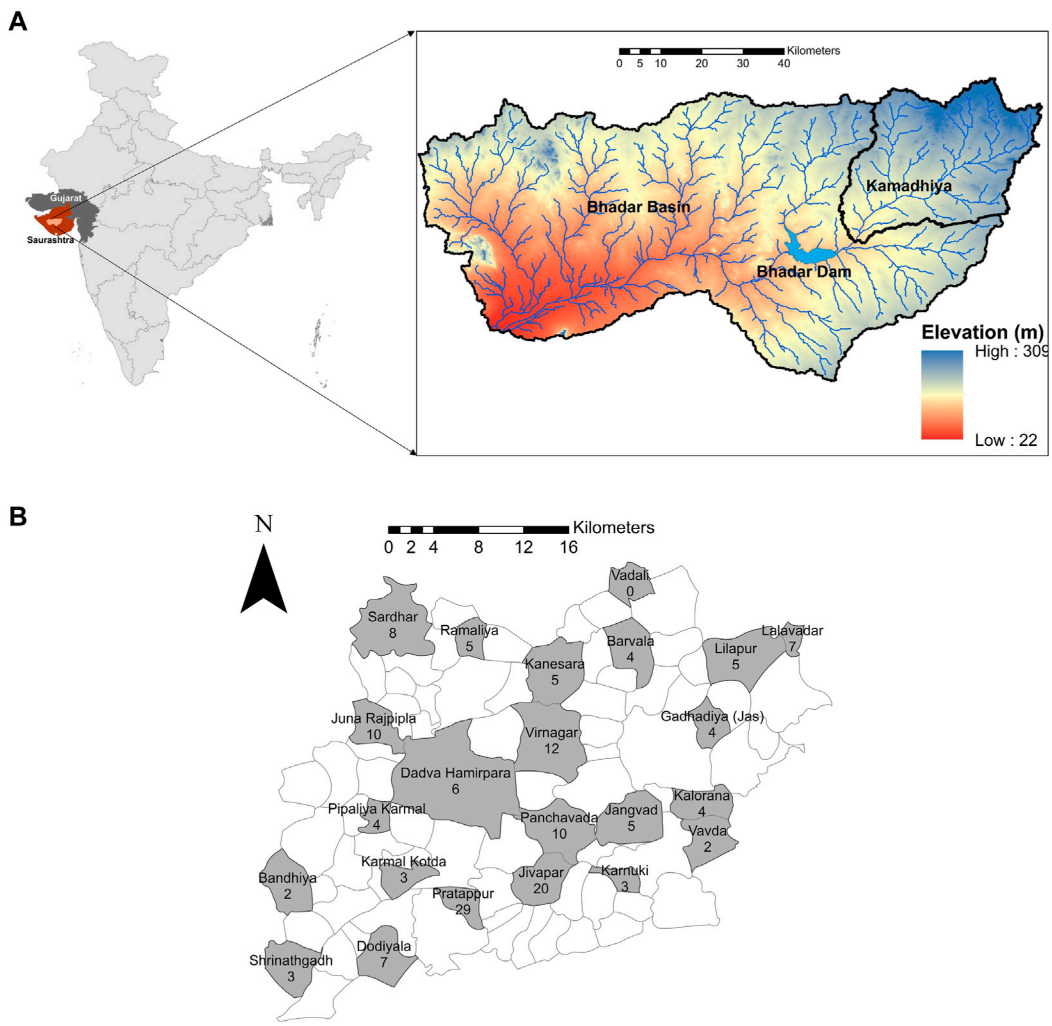

FIGURE 1
(A) Location of Kamdhiya catchment, Bhadar basin, Saurashtra region and Gujarat state in India, **(B)** Sampled villages for household survey in Kamadhiya catchment. In brackets are the number of check dams in each village (from the survey).

maintenance of RWHs? With the progressive prioritization and increased investment being made in RWHs in India and globally, the research results will contribute to making investments in RWHs more effective, equitable, and sustainable.

2 Study area

The study is carried out in the Kamadhiya catchment (1,150 km^2), located in the Saurashtra region (~6,600 km^2) of the southwestern state of Gujarat, India (Figures 1A). Kamahdiya lies in the Bhadar basin, the main river basin of the area, and drains into the Bhadar dam (Figure 1A). Administratively, the Kamadhiya catchment is predominantly located in the Rajkot district of the Saurashtra region. The catchment has a semi-arid climate with an average annual rainfall of 638 mm year^{-1} (1983–2015), with more than 90% of the rainfall being concentrated in the four monsoon months of June to September (Pai et al., 2014). Agriculture is the predominant occupation in the district with the area under crop production covering ~70% of the district area. The kharif (monsoon season starting from June to October) is the main cropping season with groundnut and cotton being the main crops The other growing season is Rabi (during the post-monsoon months of November to February) that has limited cropping area with chickpea and wheat as the main crops (DoA Gujarat, 2021).

The Groundwater is the main source of irrigation, accounting for 82% of the irrigated area (DoES, 2018). It is found at shallow depths in unconfined aquifers of the region that are characterized by parent basalt rocks of the Deccan trap formation with little primary porosity (Mohapatra, 2013). It is largely accessed from the top 20–30 m of weathered upper parts of basaltic aquifer, by wide diameter open dug wells (Patel, 2007; Mohapatra, 2013). Its storage in the shallow aquifers is mostly depleted by the end of the hydrological year with little carry over storage from year to year (Alam et al., 2022b).

2.1 Check dam development

The Saurashtra region within Gujarat has been the focus region of intensive construction of CDs (Shah et al., 2009; Patel et al., 2020). An estimated 27,000 CDs were constructed across Saurashtra before 2018 (NWRWS, 2018). This has been part of a multi-decade long groundwater recharge movement in the region (Shah et al., 2009; Mudrakartha, 2012). Though the movement had been going since 1980s, the construction of CDs accelerated following the multi-year drought of 1999–2001 (Shah et al., 2009; Alam et al., 2022b). In the Bhadar basin, within which Kamdhiya catchment is located, the number of CDs increased from 484 in 1998 to 4385 by the end of 2010 (Kamboj et al., 2011; Alam et al., 2022b). In the Kamadhiya catchment, the total number of CDs till 2006 were estimated to be 576 with a total storage capacity of 12.7 MCM (Patel, 2007). This represents a CD density of approximately 1 check dam per 2 km^2.

The CDs were implemented with government financial support under the participatory scheme "Sardar Patel Sahbhagi Jal Sanchay Yojana (Sardar Patel Participatory Water Conservation Program)" and by several non-government organizations and local leaders (Shah et al., 2009; NWRWS, 2018; Verma and Shah, 2019). Under the government scheme, 60% subsidy was provided to construct the CDs. Any group of farmers or NGOs could apply for the subsidies and many individual farmers, who could afford 40% cost, took advantage by constructing CDs close to their farms (Mudrakartha, 2012). In the region, construction of CDs is primarily done for groundwater recharge (Shah et al., 2009; Mudrakartha, 2012), which is the main source of irrigation and accounts for 82% of the irrigated area (DoES, 2018). Thus, most farmers do not directly use (lift) water from CDs.

3 Methodology

3.1 Survey

During December 2021, 492 farmers distributed across 24 villages were interviewed in the Kamadhiya catchment. The study sample was selected through a multistage random sampling procedure. First, 24 villages from a total of 88 villages lying within the Kamadhiya catchment were selected (Figure 1B; Supplementary Table SA1) using regularly distributed sampling. Thereafter, in each village, 20-22 farmers were selected for the survey using proportionate random sampling. This involves taking random samples from stratified groups in the same proportion as their proportion in the total population. Farmers were stratified into four groups: marginal (<1 ha), small (1–2 ha), medium (2–4 ha), and large farmers (>4 ha) based on farmers' land areas in the blocks where the villages are located (Supplementary Table SA2).

Interviews were conducted, after obtaining consent, with the head of households responsible for managing agricultural farms. Each structured interview lasted approximately 45–50 min and was carried out by a trained team of 10 enumerators native to the region. The questionnaire was translated into the local language (Gujarati), which was the primary language used for collecting data.

3.2 Questionnaire

The survey questionnaire consisted of two parts, 1) farmers' socio-economic characteristics and 2) farmers' perception of CD impacts and sociopsychological questions regarding the maintenance of CDs. Farmer socio-economic information (e.g., age, wealth, land) was measured on binary, ordinal, and interval scales. The questions on CDs consisted of a mix of informative questions, farmers' perceptions of CD benefits, and their behavior towards the maintenance of CDs. The detailed questionnaire can be accessed from the link given in the data availability statement.

The farmers' perception of CDs benefits was elicited through multiple questions asking about the benefits of CDs in general, benefits to main crops grown in the region, and the intensity of benefits. The questions regarding the intensity of benefits were asked for different rainfall years (dry, normal, and wet) because of high inter-annual rainfall variability in the region (rainfall in dry years ~334 mm, normal years ~564 mm, wet years ~974 mm). Recent research has shown that this significantly impacted CDs functioning with recharge in dry years being very limited and insufficient to meet the irrigation demand in the catchment (Alam et al., 2022b). Mozzi et al. (2021) have reported similar dynamics with the number of fillings being lowest in the dry years, followed by normal and wet years. However, they did not account for CDs in series so this could even be lower, especially in dry years when runoff is limited (Alam et al., 2022b).

Information regarding the behavior of farmers towards the maintenance of CDs (equated to adoption) consisted of questions on sociopsychological factors (Table 1) and were elicited based on the RANAS model (Mosler, 2012). RANAS sociopsychological factors (i.e., R-risk, A-attitude, N-norm, A-ability, and S-self-regulation) were measured with 2–4 questions on five-point Likert scales.

TABLE 1 RANAS sociopsychological factors and questionnaire with descriptive statistics.

RANAS sociopsychological factors		Question	Scale	Mean (SD)
	Behavior	Do you help maintain the check dam?	0 (never)—4 (always)	0.43 (0.8)
Risk (represent a person's understanding and awareness of the risk)	Perceived vulnerability	How high is the risk of your groundwater wells going dry in the next 5 years?	0 (no risk)—4 (a high risk)	2.11 (1.12)
	Perceived vulnerability	How high is the risk of drought in the coming 5 years?	0 (no risk)—4 (a high risk)	1.78 (1.29)
	Perceived severity	How severe will be the impact of drought on your crop production?	0 (not severe)—4 (very severe)	2.97 (0.99)
	Perceived severity	How much GW decline will impact your crop production?	0 (not severe)—4 (very severe)	2.82 (0.98)
Attitude (measures person's positive or negative stance towards a behavior)	Benefits: response efficacy	How beneficial you think is check dam during dry rainfall year for crop production?	0 (not beneficial)—4 (very high)	1.32 (1.44)
	Benefits: response efficacy	How beneficial you think is check dam during normal rainfall year for crop production?	0 (not beneficial)—4 (very high)	1.57 (1.15)
	Benefits: response efficacy	How beneficial you think is check dam during wet rainfall year for crop production?	0 (not beneficial)—4 (very high)	2.10 (1.30)
	Effort: Instrumental belief	How effortful is it to maintain a CD?	0 (not effortful)—4 (very effortful)[a]	0.81 (0.93)
Norm (measures the perceived social pressure towards a behavior)	Descriptive norm (others behavior)	What proportion of people in your village thinks maintaining check dam is helpful?	0 (almost nobody (<10%)—4 (almost all of them (>90%)	1.54 (1.04)
	Injunctive norm (others' (dis)approval)	Most people whose opinion I value think maintaining check dam is good?	0 (disapprove a lot)—4 (approve a lot)	1.86 (0.97)
	NGOs	How important are NGOs/government official opinions to you?	0 (not important)—4 (very important)	1.47 (0.87)
Ability (measures person's confidence in her or his ability to practice a behavior)	Maintenance self-efficacy	How confident are you in your financial capability to maintain the check dam alone?	0 (not confident)—4 (very confident)[b]	0.37 (0.68)
	Ability: Govt	If you want to, how confident you are in your capability to get check dam maintained by a govt dept?	0 (not confident)—4 (very confident)[b]	0.94 (0.92)
Self-regulation (measures person's attempts to plan and self-monitor behavior)	CD attention (Action control)	How much attention do you pay to the check dam condition?	0 (pay no attention)—4 (pay much attention)	1.11 (1.03)
	CD plan (action planning)	Do you have a plan on how to get the check dam maintained?	0 (no plan)—1 (moderate) – 2 (good)[c]	0.68 (0.67)

[a]Answers to effort questions where response was NA (don't know) were removed from analysis leaving 420 responses.
[b]Answers to confidence questions where the response was NA (don't know) were equated having no confidence (0.).
[c]Action planning were measured for different options (No plan, know the govt dept, know the personnel number from govt, ask gram panchayat, we have a farmers group, will do myself) and then were classified into 3 (no plan, moderate (know the govt dept; will ask gram panchayat) and good (have a farmers group).

3.3 Data analysis

Descriptive analysis is carried out to interpret the socioeconomic profile of the farmers in the region and their perception of CD benefits and impacts. This is followed by a regression analysis to understand the main determinants of farmers' behavior. The regression analysis included a first stage forced-entry linear regression considering all potential contextual factors, socio-economic and biophysical factors (e.g., distance from CDs, location in the catchment), that have a bearing on farmers' behavior (outcome variable) towards CD maintenance [measured on Likert scale of 0 (never)—4 (always)]. This is carried out to select key (significant) socioeconomic variables that impact the behavior as input to the second step of a hierarchical linear regression (Lewis, 2007).

In the second step, a hierarchical linear regression is carried out. Here, selected contextual factors (predictor variables) were used after removing factors that were found to be insignificant in the forced entry regression in the first step and sociopsychological variables were further added as predictor

TABLE 2 Socio-economic characteristics of farmers.

Characteristics	Variable	Frequency (%)
Land	<1 ha	85 (17.3%)
	1–2 Ha	155 (31.5%)
	2–4 Ha	137 (27.8%)
	>4 Ha	115 (23.4%)
HH members	0–2	52 (10.6%)
	2–4	140 (28.4%)
	4–8	240 (48.8%)
	8	60 (12.2%)
Age	<25	13 (2.6%)
	25–40	122 (24.8%)
	40–60	275 (55.9%)
	60–85	82 (16.6%)
Education	No schooling	112 (22.8%)
	Till 5th Grade	158 (32.1%)
	Till 8th Grade	144 (29.3%)
	Till 12th Grade	64 (13%)
	Bachelor and above	14 (2.83%)
Income from Agriculture (%)	<25%	47 (9.6%)
	25%–50%	161 (32.7%)
	50%–75%	100 (20.3%)
	75%–100%	184 (37.4%)
Main sources of income	Self-employed in agriculture	488 (99.2%)
	Agricultural wage labor	42 (8.5%)
	Livestock	353 (71.7%)
	Other non-agriculture related wage labor	52 (10.6%)
	Non-agriculture related business	103 (20.9%)
	Salary	44 (8.9%)
	Pension	3 (0.6%)
House type	Pucca (Brick and mortar)	322 (65.4%)
	semi-pucca (Thatched roof with brick and mortar)	151 (30.6%)
	Kuccha	18 (0.04%)
Ownership of assets	TV	413 (83.9%)
	Car	36 (7.3%)
	2-wheeler	439 (89.2%)
	Fridge	282 (57.3%)
	AC	9 (1.8%)
	Gas connection	424 (86.2%)
	none	17 (3.5%)

variables. This method has been used by other RANAS studies (Stocker and Mosler, 2015; Friedrich et al., 2017; Daniel et al., 2021, 2020a). The regression brings out the contribution of contextual factors explicitly, which in behavioral theories is often considered to be indirectly influencing behavior through sociopsychological factors (Daniel et al., 2020b).

To carry out the regression, some of the contextual factors were reclassified. Farmers based on the land area were classified (on a 1 to 4 scale) into marginal (<1 ha), small (1–2 ha), medium (2–4 ha), and large farmers (>4 ha). Farmers' education was reclassified on a 1–4 scale with 1 (No schooling), 2 (till 8th Grade), 3 (till 12th Grade), and 4 (Bachelors or Masters). A wealth index (1–4) was created based on the assets owned with 1 (all other), 2 (owning Fridge and TV), 3 (owning TV, fridge, and 2-wheeler), and 4 (owning car or air conditioning). The participation of farmers at the time of CD construction was reclassified to 0 (no participation) and 1 (all other forms of participation including labor, and financial support). Additionally, based on the elevation of villages, 24 villages were reclassified as 1 (upstream), 2 (midstream), and 3 (downstream).

4 Results

4.1 Socio-economic descriptive statistics

The surveyed farmers were distributed across marginal (17.3%), small (31.5%), medium (27.8%), and large farmers (23.4%) (Table 2). This matches with the overall proportion of these farmers in the region (Supplementary Table SA2), indicating that proportionate sampling was able to capture the diversity of farmers in the region. All the respondents were male. This also reflects the social context where questions are mostly answered by men unless women are specifically targeted. Since the information was collected on farming operations and on the perceived impact of CDs on agriculture, activities primarily being done by men in this region, therefore women farmers were not explicitly sought. Farmers in the sample were relatively senior with an average age of 49 years and 62% were above the age of 40. Education was low among the farmers with 22% having no schooling and 61% of the farmers had 8 years or less of schooling.

The income from crop production contributes more than 75% of total income for 37% of the farmers. This shows that other sources exist for generating income such as livestock production (reported by 71.7% farmers), followed by non-agriculture-related business (20.9%), non-agriculture wage labor (10.5%), salary (8.9%) and agricultural wage labor (8.5%). Most of the farmers that were interviewed had pucca (brick and plastered) or semi-pucca houses. In terms of wealth, most of the farmers owned a television (83.9%), 2-wheeler (89.2%), and a cooking gas connection (86.2%). However, only a few farmers owned a car (7.3%) or an air conditioner (1.8%).

4.2 Farmer perception of check dams' benefits and impacts

Overall, there are on an average 12 CDs per village in the catchment (Supplementary Table SA3). The median number of CDs reported in a village ranged from 3 to 40 with only 9 villages having less than 10 CDs. However, data shows that there is a large variation in the number of CDs reported by farmers within a village (Supplementary Table SA3). This shows that farmers either do not know about all the CDs in their village or their answers do not relate to the village administrative area but to their knowledge of nearby areas (which may overlap with other villages).

Most CDs were reported to be built during the period 2000–2010 (44%) (Supplementary Table SA4), coinciding with the period following the multi-year drought (1999–2001) when CD construction accelerated. There has been a decline in the number of new CDs being built in recent years, with only 3.5% of CDs reported being from the period 2015–2020. When asked about the participation of farmers in the construction of CDs, 91.2% of farmers reported playing no role in the construction of CDs. Only 8.8% reported contributing towards construction mainly through providing labor (5.2%) followed by a financial contribution (2.8%) and material contribution (0.8%).

4.2.1 Farmers benefiting from check dams

Overall, 61% of the farmers reported that they benefitted from CDs. The results also show that the proportion of farmers benefiting from CDs decreases with distance. Overall 87.3%, 82.5%, 70.7%, and 49.5% of farmers reported benefitting at a distance of <250, 250–500, 500–1,000, and >1,000 m, respectively from the closest CD. Of the sampled farmers, a majority of the farmers (~61%) have farms at > 1,000 m from CDs and only ~20% reported nearest CD at a distance of less than 250 m. The relation of CD benefits with distance was found to be significant (chi-square test: $\chi^2 = 55.3$, p-value < 0.05). There was no significant difference in reported CD benefit with increasing land size of farmers in the sample. Also, there was no significant relation (using OLS) between proportion of farmers reporting benefits from CDs (Supplementary Table SA3) and the median number of working CDs in a village.

4.2.2 Type of check dam benefits

The farmers who reported benefitting from CDs, indicated that the main benefits were increased groundwater levels (93.3% of the farmers) and water lasting longer in the wells (81.6% of the farmers) (Figure 2A). This was followed by 40% of the farmers (26% in the rabi season, 13% in the kharif season and 1% in the summer season) reporting an increase in water availability for

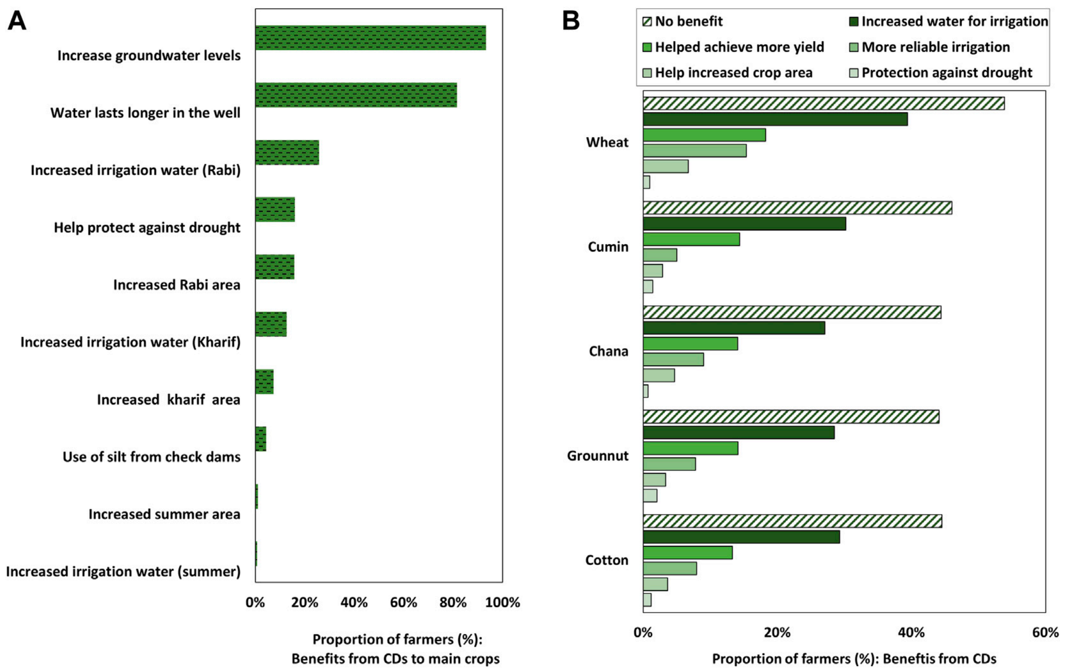

FIGURE 2
(A) Distribution (as a proportion of farmers) of the overall reported benefits from CDs; **(B)** Distribution (as a proportion of farmers) of the reported benefits from CDs to main crops.

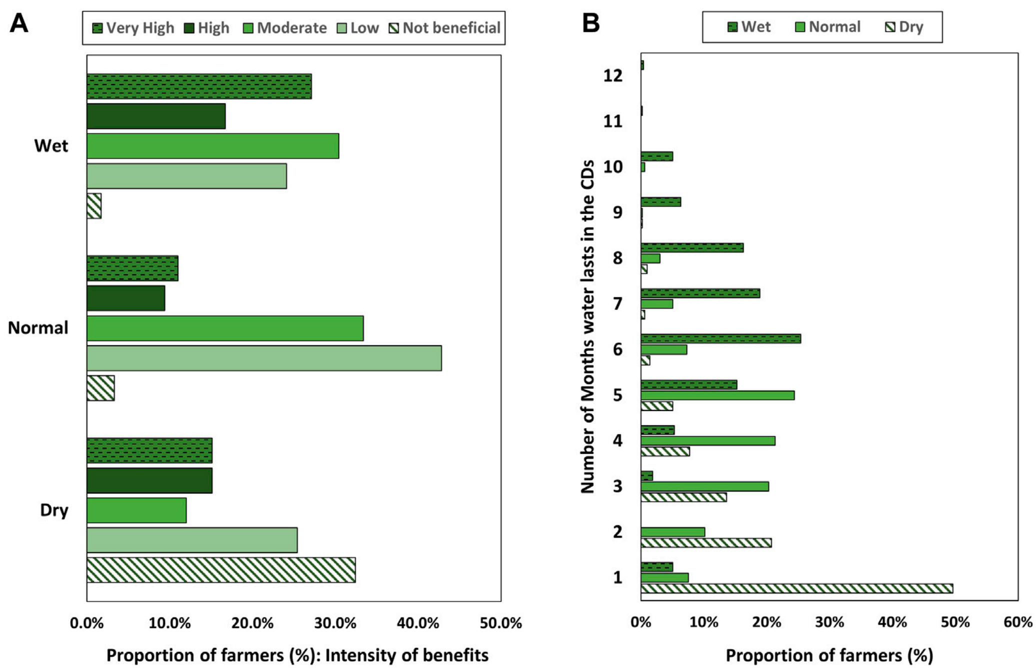

FIGURE 3
(A) Distribution (as a proportion of farmers) of the intensity of benefits reported for dry, normal, and wet years; **(B)** Distribution (as a proportion of farmers) of the number of months till which water lasts in CDs for dry, normal and wet years.

TABLE 3 Results of forced entry regression on contextual factors.

	B	SE B	β
	R^2 = 0.28		
(Intercept)[a]	0.66	0.32	0.00*
Farmers land area	0.01	0.00	0.14**
Farming experience	0.00	0.00	−0.04
Agriculture income proportion	−0.01	0.00	−0.15***
CDs direct water use	−0.62	0.16	0.17***
Distance from CDs	0.00	0.00	−0.16***
Education	0.10	0.06	0.09
Wealth	0.07	0.04	0.07
Irrigation access	−0.10	0.20	−0.02
Location (upstream—downstream)	0.07	0.04	0.07
House type	0.12	0.06	0.09*
Participation in CD construction	0.98	0.12	0.34***

[a]The point where the function crosses the *y*-axis.
[b]Variance inflation factor (VIF) was estimated to check for multicollinearity. All values were less than threshold of 5.
*$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$.

irrigation. Also, 24% of the farmers reported increasing crop area (16% in the rabi season, 7% in the kharif season, and 1% in the summer season). Only 16% of the farmers directly reported protection against drought as a benefit of CD (Figure 2A). However, the top three benefits reported by the farmers are direclty linked to the increased capacity to mitigate the impacts of droughts. About 4% of the farmers also reported spreading the silt from the CDs on their fields. Also, only 4% of the farmers reported directly using water from the CDs which is in line with field evidence that these CDs are primarily for the purposes of groundwater recharge.

In response to the specific question of how CDs benefitted their main crops, results showed that increased water for irrigation (29%–39%), helped them achieve more yields (13%–18%), and increased reliability of irrigation (8%–15%) were the most often reported answers (Figure 2B). This shows that farmers perceive the primary impact of CDs on groundwater which then translates to the secondary impacts of an increase in irrigation water availability (and reliability) and enhanced yields for crops. Protection against droughts was reported to be a direct benefit by only ~ 1%–2% of the farmers but the increase in availability (and reliability) of irrigation water can be considered as safegaurds against droughts. Further, 44%–53% of the farmers no benefits from CDs when asked about impact of CDs for each crop they grow.

4.2.3 Check dam benefits in dry, normal, and wet years

Of the farmers who reported benefits from CDs, Figure 3A shows the intensity of benefits [measured on Likert scale of 0 (not beneficial)—4 (very high)] reported by them. The intensity of benefits reported was highest for the wet years, with 44% and 30% of farmers reporting very high or high and moderate levels of benefits, respectively. For normal years, the intensity of benefits was relatively lower with most farmers reporting low (42.8%) or moderate (33.3%) levels of benefits and only 20% of the farmers reported high or very high benefits. For dry years, intensity of benefits reported was lowest. Most farmers (32.4%) reported no benefits in followed by 25% reporting low benefits.

The relatively low benefits in dry years and high benefits in wet years correlate well with reported availability of water in the CDs (visible on surface) by farmers. Since the farmers do not use the water directly from the CDs, the availability of water in CDs indicates the water that is available for recharge. Most of the farmers reported that in dry years water lasts only for less than 3 months (till June to August) with June being the start of the monsoon season. On the other hand, most farmers reported water availability for ~8 months (till January) for the wet years and for ~5 months (till October) for the normal rainfall years (Figure 3B). This reflects no or limited availability of water for recharge in dry years as the rainfall is scarce.

4.3 Maintenance of check dams

The sustainability of CDs requires regular maintenance to repair damages to structures from debris and de-siltation. Without maintenance, its performance decreases over time and ultimately, becomes dysfunctional. The results show that out of 12 CDs reported per village, only 6.9 CDs were working. This means that about 40% of the CDs were not operational. Results also showed that farmer participation in the maintenance of the structures was quite low. Most farmers (72.8%) reported never doing any activity to maintain the CD whereas 21% reported doing it only sometimes. In the next sections, the contextual and sociopsychological factors that influence farmers' behavior toward the maintenance of CDs are discussed.

4.3.1 Contextual predictors impacting farmer's behavior towards check dam maintenance

Table 3 shows the results of forced linear regression on contextual (socio-economic and biophysical factors) predictors of farmers' maintenance behavior. The model explains 28% of the variance. Results show that education, wealth, participation in CD construction, proximity to CD, and direct water use from CD are the significant factors ($p \leq 0.05$) influencing farmers' behavior toward its maintenance. The participation in CD construction is the most influencing factor (β = 0.34) followed by direct water use (β = 0.17) and distance from CDs (β = −0.16). The negative sign for the latter shows that farmer's behavior towards maintenance is negatively correlated with distance from CDs i.e., the larger the distance, the lower the participation in maintenance. Farmers land area (β = 0.14), proportion of income from farming (β = −0.15) and house type (β = 0.09) are significant socioeconomic factors. Farmers with more diversified incomes show more inclination toward maintenance as indicated by the negative sign for the proportion of income from farming in the regression (Table 3).

4.3.2 Sociopsychological predictors impacting farmers' behavior towards check dam maintenance

Hierarchical regression was performed after incorporating important (significant) contextual factors identified in the forced regression in the first step and RANAS sociopsychological factors in the second step. The addition of sociopsychological factors increased the percentage of variance of the outcome variable explained by the model to 53% (Table 4). The attitude towards effort (instrumental belief) and attention to the state of maintenance of CDs (self-regulation) are the only two sociopsychological factors that influence farmers' behavior towards the maintenance of CDs. Attitude (β = 0.29) and self-regulation (β = 0.23) were more influencing than the contextual factors. All other RANAS sociopsychological factors (Table 2) including farmers' risk perception, social norm, attitude towards CD benefits, and ability factors were found to be insignificant towards influencing farmers' behavior of maintaining CDs.

5 Discussion

5.1 Check dam benefits

5.1.1 Drought impact mitigation

The results show that the main perceived benefits of CDs are enhanced water availability and reliability that helps farmers to expand their crop and irrigated area (Figures 2, 3). However, these benefits are mostly accrued in wet years and are least in dry years (Figure 3A) when irrigation demand is the highest. This is due to limited rainfall and runoff in the dry years that limits inflows to the CDs (Alam et al., 2022b; Mozzi et al., 2021). Thus the duration of water availability in CDs decreases from 8 months in wet years to only 3 months in dry years (Figure 3B). It is intuitive that most farmers do not perceive a CD as an intervention that directly mitigates the impacts of drought (Figures 2A,B). However ~30% of the farmers do report high or very high benefits even in dry years (Figure 3A). This shows that the presence of CDs does add, though little, to drought adaptation if compared to the villages with no CDs.

These results corroborate with the findings of water balance study in the catchment that showed that recharge from CDs was insignificant in dry years and crop demands remained unmet (Alam et al., 2022b). This is because in semi-arid regions with shallow basaltic hard rock aquifers having little primary porosity, CDs or water storage structures have limited capacity to recharge aquifers sufficiently to mitigate the impact of droughts (Kumar et al., 2008; Kumar and Perry, 2018; Enfors et al., 2008; Ogilive et al., 2016; Ogilive et al., 2019; Alam et al., 2022b). Similar conclusions have been drawn in other semi-arid regions of the world. For example, Enfors et al. (2008), Ogilive et al. (2016), and Ogilive et al. (2019) assessed RWHs in Tanzania (locally termed Ndiva system) and Tunisia respectively. The authors showed that the low storage capacity of small reservoirs, often the case of RWH systems, limited their capacity to augment surface water supplies or recharge groundwater sufficiently to provide reliable irrigation supply and did not lead to significant increases in farmers' capacity to cope with droughts. Thus, in the situation of limited possibilities to increase water availability especially during dry years, these efforts need to be strengthened in tandem with other drought management strategies such as crop diversification, agriculture insurance, off-farm income and drought tolerant crops and varieties.

The results show that rather than drought mitigation, the main benefits of CDs are accrued in good rainfall years where additional water availability makes irrigation more reliable. This helps mitigate the impact of short dry spells and leads to increased crop cultivation in the post-monsoon dry season. This is in line with the hypothesis and results by Shah et al. (2009) for the study region and by Ogilive et al. (2019) in Northeast Brazil. This emphasises that small storage RWHs are more suitable to support supplemental irrigation and cannot be expected to sustain widespread intensive irrigation (Ogilive et al., 2016; Ogilive et al., 2019).

In certain situations, carryover benefits of CDs from good rainfall years to dry years may enhance RWHs capacity to mitigate water scarcity in dry years (Garg et al., 2020; Singh et al., 2021). This may happen in the case of RWHs with relatively larger storage capacity, enabling farmers to capture more and store longer (Ogilive et al., 2016; Ogilive et al., 2019). Additionally, in places where cropping and irrigation intensity is limited, recharged water in wet years may remain available for irrigation in dry years (Garg et al., 2020; Singh et al., 2021). For example, a study by Garg et al. (2020) in semi-arid central India showed that even in dry years with negligible runoff, groundwater storage (measured by the number of wells going dry) was much higher (low number of wells going dry) in the watershed with RWHs compared to control watersheds. Singh et al. (2021) in the same region showed that recharge in wet years can sustain for 2 years. However, as observed by Alam et al. (2022b), in an intensively irrigated area like the one studied here where groundwater storage in shallow aquifers is mostly depleted by year end, any such carryover impact is less likely. This was also the finding of Enfors et al. (2008) who did not find any carryover effect from preceding seasons in Tanzania as the irrigation systems were substantially overused.

5.1.2 Equity of benefits

Previous studies focusing on CD benefits largely focused on regional or watershed scales relying on assessing the dynamics of groundwater levels and rainfall (Patel et al., 2020; Shah et al.,

TABLE 4 Results of Hierarchical Regression with Contextual (model 1) and Sociopsychological factors (model 2) for farmers behaviour towards CD maintenance.

	B	SE B	β
	Model 1 (R^2 = 0.26)		
(Intercept)[a]	0.90	0.22	0.00***
Farmers land area	0.01	0.00	0.15***
Agriculture income proportion	0.00	0.00	−0.15***
Direct water use from CDs	−0.73	0.16	0.20***
Distance from CDs	0.00	0.00	−0.17***
House type	0.20	0.06	0.14***
Participation in CD construction	0.99	0.12	0.34***
	Model 2 (R^2 = 0.53)		
(Intercept)	−0.24	0.22	0.00
Farmers land area	0.00	0.00	0.08*
Agriculture income proportion	0.00	0.00	−0.01
Direct water use from CDs	−0.40	0.14	0.11**
Distance from CDs	0.00	0.00	−0.09*
House type	0.14	0.05	0.10**
Participation in CD construction	0.55	0.11	0.19***
Perceived risk: GW depletion	−0.02	0.03	−0.03
Perceived risk: Drought	0.04	0.03	0.06
Perceived severity: Drought	0.05	0.03	0.06
Perceived severity: GW depletion	0.03	0.03	0.03
Descriptive norm (others behavior)	0.02	0.03	0.03
Injunctive norm [others' (dis)approval]	0.07	0.04	0.08
NGO's opinion	−0.04	0.03	-0.04
Ability: Maintenance self-efficacy	−0.03	0.05	−0.03
Ability: Govt	0.04	0.04	0.05
Attitude effort (instrumental belief)	0.29	0.04	0.34***
Attitude: Benefit dry year	−0.01	0.03	−0.02
Attitude: Benefit normal year	−0.04	0.05	−0.06
Attitude: Benefit wet year	−0.04	0.03	−0.07
CD attention (action control)	0.18	0.04	0.23***
CD plan (action planning)	0.07	0.05	0.06

[a]The point where the function crosses the *y*-axis.
[b]Variance inflation factor (VIF) was estimated to check for multicollinearity. All values were less than threshold of 5.
*$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$.

2009). This ignores the equitability of the distribution of benefits within the population. The results show that despite the high density of CDs in the region, 40% of the farmers still reported no benefits from CDs. This percentage was higher (~50%) when asked about specific benefits for the main crops grown. This is similar to the results from Shah et al. (2001) who estimated that ~80% of households in the villages where CDs were built did not benefit from CDs.

Also, a decrease in benefits with distance from CDs (Section 4.2.1) reflects an inequitable distribution of benefits skewed towards farmers nearest to the streams where the structures are constructed. This skewed distribution was also reflected in a study by Shah et al. (2021) in Maharashtra where farmers' responses showed that benefits of lowland stream-course work (e.g., check dams) remained concentrated in nearby areas and were not achieved when located far away from CDs in upland areas. Deora and Nanore (2019) studying RWH systems in Maharashtra, India also showed that recharge structures benefits on streams are limited to agriculture fields that are downstream and close to the streams, leaving a large portion of agriculture area with no benefits.

This skewed distribution of benefits is more pronounced in watershed development projects. A high proportion of works in watershed projects are concentrated on hard adaptation options such as water harvesting structures, which are also more costly structures relative to other watershed works (e.g., *in-situ* soil moisture conservation, land area treatment) (Shah et al., 2021; Sharma, 2007; Shah, 2001; Singh, 2018). Thus, a large proportion of project budgets may go on to benefit a small proportion of farmers. Hence, there is need for a more holistic and balanced approach, acknowledging biases towards RWHs in projects and emphasising adoption of a wider suite of area-based practices focusing on *in-situ* conservation (e.g., forestry, contour bunds, trenches) available for implementation. This will encourage more equitable distribution of benefits.

Additional concerns are that water harvesting and recharge interventions may benefit relatively influential and richer farmers who have the financial capacity to invest in irrigation infrastructures and other agronomy investments (Bouma et al., 2011; Calder et al., 2008; Shah et al., 2021). While our results do not find any significant correlation of reported benefits with land size, this does not exclude other socio-economic and political characteristics that wield social power and may skew benefits. For example, the distribution of land in villages is not random and land acquisition and settlement over time leads to marginalized communities occupying less favorable lands (low fertility, limited water) (Sharma et al., 2008). Thus, inequitable distribution of lands and groundwater rights bundled with land ownership (Sharma, 2007) may mean that landless or marginalized communities located away from drainage lines do not benefit from these interventions. More research is needed in the region to unravel this phenomenon.

5.2 Sustainability of investments

With a high proportion of project budgets allocated to hard adaptation measures such as CDs, it is critical to ensure their sustainability. This requires regular maintenance and desiltation to assure their structural integrity and optimum functioning. However, the sustainability of RWH structures after the withdrawal of project support has remained a challenge (Sharma, 2007; Singh, 2018; Deora and Nanore, 2019). Results also show that already 40% of CDs are not working. This seems to arise from the ageing of these structures (40% of CDs are over 20 years old) and lack of maintenance with 72.8% of farmers reported no activity to maintain the CDs. The average life span of CDs (masonry ones) is expected to be ~20 years (Lee et al., 2022) but is dependent on regular maintenance. Dysfunctional CDs and limited construction of new CDs, threaten the long-term benefits that could be accrued from these investments. Yet the limited involvement of farmers in maintenance and neglect of infrastructure is not uncommon (Agoramoorthy et al., 2009; Deora and Nanore, 2019).

The regression analysis shows that the participation of farmers during the construction of CDs is a key determinant of farmers' behavior towards maintenance. Public participation as a key indicator of post project success has been well established in previous research and plays a key role in watershed program guidelines (Sharda et al., 2005; Sharma, 2007; Joshi et al., 2008; Singh, 2018; Deora and Nanore, 2019). Thus, low maintenance of structures by farmers aligns well with results that also show limited participation of farmers (~92% did not participate in any way) during the construction of CDs. While many of the CDs are old, the results show that ~77% of sampled farmers were >18 years old at the time CDs (ones nearest to them) were built. This is despite the participatory nature of government schemes where farmers were expected to contribute ~40% of CD costs. Mudrakartha (2012) reflects that this largely happened because local contractors secured the work in the names of local farmers (subsidising the farmers contribution) and made profit. This also led to the weakening of the participatory nature of the programme where farmers viewed these structures as government structures and lost the sense of ownership (Mudrakartha, 2012). This heterogeneity in the implementation process and dynamics may explain variation in maintenance of CDs.

The significance of socio-economic factors including wealth (land area, house type) may indicate that CD maintenance is effortful and an expensive task that may be difficult for individual farmers to carry out. This is also highlighted by the fact the farmers with more diversified income have more tendency to maintain (Table 4). This could be because farmers with more diversified income can allocate a higher share of their total income to tasks requiring financial commitments such as CD maintenance. Other studies have also shown that a more diversified income is linked to higher adoption of new farm technologies such as drip irrigation (Nair and Thomas, 2022). To overcome the financial barrier, research has highlighted the role that community institutions such as farmers' groups can play in ensuring the sustainability of such investments (Agoramoorthy et al., 2009; Singh, 2018). While the survey data analysed here did not elicit any information on the existence of such groups in the region, none of the farmers reported being part of a farmers group in response to the question on "plan to maintain check dams." Other significant contextual (biophysical) factors include direct use of water from CDs and distance from CDs which are related to the benefits arising from CDs.

Limited community participation and non-existent farmer groups calls for a stronger emphasis and monitoring of post project exit protocols as already outlined in guidelines for watershed programs in India (NRAA, 2011; DoLR, 2021). This includes the formation of watershed committees and creation of watershed development funds for future maintenance, and its convergence with other development programs to pool resources for major repairs and maintenance (Sharda et al., 2005; Joshi et al., 2008).

In terms of sociopsychological factors, only instrumental belief towards the efforts that it takes to maintain CD and self-regulation (action control) reflecting attention paid by farmers towards CD state of repair comes out to be significant factors influencing the behaviour of farmers towards its maintenance. In terms of effort, the results are counter-intuitive because farmers that perceive CD maintenance as more effortful show higher participation in its maintenance. This is similar to what Stocker and Mosler (2015) found where the perceived increase in the effort was related to a stronger habit of cleaning with soap and water. This could be because of the reverse effect, where farmers who regularly contribute towards CD maintenance are more aware of how effortful the task of maintaining a CD is. Behavioral change techniques such as communication and visualization of CD state of repair and a more systematic recording of the maintenance behavior (increasing self-regulation) can lead to more farmers contributing to its maintenance. The formation of farmers groups can bring down the effort (perception associated with it) required for the maintenance of CDs.

5.3 Unintended consequences: Human-water dynamics

Annual crop area and irrigation data shows that cotton (main kharif irrigated crop in the region) area has increased by ~124% in the years following 2002 (the period also coincides with accelerated construction of CDs) and the irrigation coverage has increased from 64.2% to 85.4% (DoA, 2021; Alam et al., 2022b). This translated to higher demand and in the case of limited increase in supply, as is the case for dry years, increased supply-demand deficits. This potentially led to higher vulnerability to droughts (Alam et al., 2022b). This study provides an indirect link between the increase in irrigation demand and increased (perception of) supply. The results show that the primary benefit to crops reported by farmers includes increased (perceived) availability of irrigation followed by a small set of farmers also reporting an increase in cropped area (Figures 3A,B). In the region where crop production is limited by water availability (especially in the post-monsoon season), this increased supply (and its reliability) of irrigation water directly links to increased intensity of irrigation in both pre and post monsoon seasons (leading to increased yields). This to an extent has led to increased cultivation of post monsoon crops which are completely dependent on water. Earlier research in the region (Shah, 2001) has also shown that additional water availability has led to an increased overall irrigated area under more water-intensive cotton crops. Studies in other semi-arid regions have also found that farmers have increased their cropping intensity and crop diversification in agriculture farms that were near such RWH structures (Deora and Nanore, 2019).

This shows the existence of supply-demand feedbacks where increased supply (from RWH or another supply measure) leads to more demand, offsetting the benefits from the increased supply (Glendenning et al., 2012; Scott et al., 2014; Di Baldassarre et al., 2018). The increase in demand, associated with increased irrigation and cropping intensity may lead to greater shocks in dry years when water availability remains low and CDs are less effective. However, the argument can be made that the additional benefits accrued from increased production in normal and wet years supported by CDs outweighs the losses in dry years. Additionally, there is a risk that farmers may acquire deep borewells, tapping deeper aquifers, to continue supporting increased irrigation (area) of good rainfall years. Survey results showed (not given in results) that already 25% of farmers own deep borewells in addition to dug wells. Thus, to ensure the long-term sustainability of the systems, there is a need to supplement supply interventions with greater emphasis on water demand management interventions (e.g., more efficient irrigation, less water-intensive crops, improved water management practices) and groundwater governance. This is often lacking in such programs (Singh, 2018) and is reflected in our survey where only ~10% of farmers reported using drip irrigation for irrigation.

Overall, this reflects two-way feedback that is endemic to human-water systems where both human and water systems feedback to each other and co-evolve. For example, Ribeiro Neto et al. (2022) showed how small man-made reservoirs in Northeast Brazil, made by the local population as a coping mechanism to drought, induce and modify drought events. These unintended consequences are necessarily not always negative. For example, Enfors et al. (2008) found that while RWHs in Tanzania did not directly change the coping capacity to drought but it incentivized nearby farmers to have better farmland management practices with more investment in nutrient management and soil conservation.

There is an inherent need to model these two-way human-water system feedbacks to understand and predict the impacts of RWH systems, without which investments can exacerbate and reinforce current inequalities and lead to long-term natural resource degradation. More recent interdisciplinary approaches such as sociohydrology can help to understand and disentangle the dynamics and help better plan these RWHs (Sivapalan et al., 2012; Pande and Sivapalan, 2017).

5.4 Recommendations

The findings of the study call for a more nuanced and site-specific approach towards the implementation of RWHs for effective, equitable, and sustainable implementation outcomes. First, there is a need for clear communication and realistic assessment and expectation of the potential benefits of RWHs. This is especially so for semi-arid regions with intensively irrigated areas and hard rock aquifers having little primary porosity, where drought mitigation potential of CDs remains limited. Second, the implementation of CDs should be complemented by greater emphasis on other drought management strategies (e.g., demand management, insurance, off-farm income). The special focus should be on water demand management for more effective use of stored/recharged water and to avoid unintended consequences of supply-demand feedbacks. Third, equitability concerns regarding the distribution of the benefits (spatially and among socio-economic groups) should be evaluated. For a more equitable distribution of benefits, a holistic suit of interventions should be implemented with equal emphasis on a wider suite of area-based practices focusing on *in-situ* conservation (e.g., forestry, contour bunds, trenches). Finally, to ensure the sustainability of projects through the maintenance of such structures, the participation of farmers (beyond consultations) should be encouraged to build a sense of ownership, and post-project exit protocols (forming water user groups, maintenance funds) should be strictly adhered to. Behavioral change techniques (communication, visualisation of the state of CDs) can assist in raising the awareness of farmers and make them more responsible towards maintenance.

6 Conclusion

RWHs through various interventions (including CDs) are increasingly being promoted and adopted as an adaptation measure to build resilience to cope with dry spells and droughts, especially in arid and semi-arid regions of the world. This study analysed the perception of the farmers' about the benefits of CDs, the equitability of such benefits, and the sustainability of CDs in the semi-arid Saurashtra region of Gujarat, India, where CDs have been extensively implemented for more than 30 years. The results of the study showed that the key perceived benefit of CDs is increased water availability for irrigation that is realised through increased groundwater levels and longer availability of water in wells. This helps farmers to achieve more yield and increase area under crops. However the benefits are mostly accrued in wet years, followed by normal years and least in dry years. CDs are therefore not perceived as a drought mitigating interventions. This is due to low runoff in dry years limiting the water inflow to the CDs and underlying hard rock aquifers having limited inter-annual carry over capacity. Also, the benefits of CDs are inequitably distributed and are concentrated to farmers who are near to the streams where CDs are built. Overall ~40%–50% of farmers reported accruing no benefits from CDs despite the high density of CDs. The results also reported that ~40% of total CDs are not functional and most of the farmers (72.8%) do not participate in any maintenance activity. The regression analysis showed that both contextual (e.g., participation during CD construction, farmers' land area) and sociopsychological factors (e.g., attitude towards CDs, attention they pay to the CDs condition) significantly influenced the behaviour of farmers. The perception of an increase in water supply from CDs, as seen in good rainfall years, may lead to increased irrigation and cropping intensity which increase the risk of greater shocks in dry years (when increase in water availability is limited). This could be worsened by the lack of maintenance of CDs and over the long-term may lead to unsustainable solution of overexploitation of deeper aquifers with more farmers drilling deep groundwater wells. The study therefore calls for a more holistic implementation of drought mitigating measures with balanced implementation of supply enhancing and demand management interventions (Ogilvie et al., 2016).

Data availability statement

The data presented in the study are deposited in the figshare repository: https://figshare.com/articles/dataset/Survey_questions_and_data/21587382.

Ethics statement

The studies involving human participants were reviewed and approved by Human Research Ethics Committee TU Delft (http://hrec.tudelft.nl/). The patients/participants provided their written informed consent to participate in this study.

Author contributions

MA: Writing—original draft, methodology, formal analysis, data curation. MM: Supervision, result interpretation, writing—review and editing. AS: Supervision, writing—review and editing. DD: Methodology, result interpretation, writing—review and editing. SP: Supervision, methodology, result interpretation, writing—review and editing.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.1043896/full#supplementary-material

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