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Subsidies alone are not enough to increase adoption of agricultural water management interventions

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The adoption of agricultural water interventions for climate change adaptation has been slow and limited despite their established efficacy and benefits. While several studies have identified socio-economic, biophysical, technological and institutional factors that influence adoption, psychological factors have often been overlooked. This study examines the socio-economic and psychological factors, using RANAS behavioral model, that influence the adoption of agricultural water interventions in the semi-arid region of Saurashtra in India. Two contrasting and dominating agricultural water interventions in the area: drip irrigation and borewells are evaluated. Despite subsidies being available for drip irrigation systems, the adoption rate remains low (~16% adopting rate) compared to borewells (~24.5% adoption) with no subsidies reflecting farmer's preference for supply augmentation measures over demand management. Incorporating psychological factors in the analysis improved the explanatory power of the logistic model by almost threefold, underscoring the significance of psychological factors in explaining farmers' adoption decisions. Based on the logistic model, major factors determining farmers adoption behaviour identified are farmer's perceived ability, risk preference and positive beliefs about the technologies along with socio-economic (e.g., land size) and biophysical factors (e.g., proximity to water). The study recommends a multi-pronged approach to increase the adoption of interventions, including augmenting subsidies with efforts on extension services, post-adoption services, training, and awareness campaigns to build farmers' capacity and raise awareness.

KEYWORDS

agriculture water management, drip, borewell, adoption, RANAS, subsidy

1 Introduction

Agriculture with a strong dependence on weather is highly vulnerable to climate change (FAO, 2021; Sikka et al., 2022). With changing climate intensifying hydroclimatic extremes of floods and drought, adaptation in agriculture is extremely important (United Nations, 2019; IPCC, 2022). Without adaptation, agricultural yields could decrease by 30% by 2050, impacting livelihoods and food security, especially in less developed countries where smallholder farmers have limited capacity to adapt (GCA and WRI, 2019). Given the centrality of water in climate change adaptation efforts, climate smart agriculture water management is critical to building water resilience and adapting to climate change (Sikka et al., 2022). The efficacy and benefits of a range of climate smart agriculture water interventions for adaptation have been widely reported and established (Evans and Giordano, 2012; Alam et al., 2021; Sikka et al., 2022).

The successful scaling of these interventions is needed to achieve transformational and visible impacts in building climate change adaptation (Aggarwal et al., 2018; Sikka et al., 2022). However, the widespread adoption of agricultural water management interventions and technologies has been slow and limited (Shiferaw et al., 2009; Palanisami et al., 2015; Alam et al., 2021). Multiple studies over time and in different contexts have evaluated the factors influencing the uptake of different adaptation strategies and technologies in agriculture (Palanisami et al., 2011; Reddy, 2016; Pathak et al., 2019; Balasubramanya et al., 2023). Several factors including socio-economic (e.g., land size, experience), biophysical (e.g., soil), technology (e.g., cost, availability), and institutional (e.g., capacity building, subsidies) have been identified (Pathak et al., 2019; Nair and Thomas, 2022; Balasubramanya et al., 2023).

However, psychological factors have been often overlooked in many studies (Namara et al., 2007; Nair and Thomas, 2022; Balasubramanya et al., 2023). This is a gap as several studies have shown that psychological factors significantly influence the adoption of interventions (Daniel et al., 2020; Hatch et al., 2022; Alam et al., 2022a). For instance, farmers' perceived behavioral control, belief about cost and benefits, and risk perception have been shown to significantly influence their adoption decisions (Yazdanpanah et al., 2014; Arunrat et al., 2017; Alam et al., 2022a,b). Thus, neglecting psychological factors can lead to a lack of understanding of why some farmers adopt interventions while others do not, despite similar socio-economic and environmental conditions.

Several behavioral theories, grounded in social science, exist to evaluate the influence of psychological factors on farmers' adoption behaviors (Schlüter and Pahl-Wostl, 2007; An, 2012; Alam et al., 2022b). The risk, Attitude, Norms, Abilities, and Self-regulation (RANAS) model (Mosler, 2012) is one among them. The RANAS model assumes that multiple socio-psychological factors (i.e., risk, attitude, norm, ability, and self-regulation) impact behavioral outcomes (i.e., behavior, intention, use, and habit). Although initially developed for the WASH sector, the RANAS model is being increasingly used to understand farmer irrigation behavior or adoption of water management interventions (Stocker and Mosler, 2015; Daniel et al., 2020; Hatch et al., 2022; Klessens et al., 2022; Alam et al., 2022a). RANAS's strength is that it combines important socio-psychological factors from other important behavioral theories, can be adapted for a range of behaviors, and provides a systematic approach with a standardized questionnaire (Callejas Moncaleano et al., 2021).

This study, using the RANAS behavioral model, examines the factors that influence the adoption of agricultural water interventions in a semi-arid region (Saurashtra) in India. Specifically, adoption of two dominant and contrasting agricultural water interventions in the region: drip irrigation and borewells are analyzed. Drip irrigation, increasing efficiency of on farm water application, is a demand management strategy and is extensively promoted by the government with enabling policies and subsidies (Nair and Thomas, 2022; Sikka et al., 2022). While micro irrigation generally consists of both drip and sprinkler irrigation, in the studied region, drip irrigation is the dominant form, and therefore, we have used the terms "drip" and "micro irrigation" interchangeably in the paper. On the other hand, drilling borewells to tap deeper aquifers is a supply-augmenting intervention that farmers adopt in response to the drying of wells or depletion of aquifers (Kattumuri et al., 2017; Patil et al., 2019). Access to groundwater has played a crucial role in expanding irrigation and production globally, especially in South Asia (Mukherji, 2020) and now increasingly in Africa (Cobbing and Hiller, 2019). However, over time, this has led to the depletion of aquifers (Mukherji, 2020).

This paper evaluates the factors that govern the adoption of drip irrigation and borewells in the Saurashtra region. The findings of this study provide insights into the key factors that need to be addressed to promote the adoption of water interventions among farmers. It informs the development of effective policies and programs to improve water management in the region and elsewhere.

2 Study area

The study area is the Kamadhiya catchment located in the Saurashtra region of Gujarat state in India (Figure 1). The region is characterized by a semi-arid climate, low rainfall [average of 638 mm year^{-1} (1983–2015)] with high evaporation and high-water demand. There is large intra- and inter-year rainfall variability that impacts the agriculture in the region, which covers ~70% of the catchment area (Alam et al., 2022c). More than 90% of the rainfall is concentrated in the four monsoon months of June to September (Pai et al., 2014). The main crops grown in the region are cotton and groundnut during the Kharif season (the monsoon season, starting in June and ending in October) and chickpea and wheat during the Rabi season (the post-monsoon season, starting in November and ending in February/March). The lack of water during the post-monsoon season limits crop intensity (Alam et al., 2022c).

Groundwater is the main source of irrigation in the region, covering ~82% of the irrigated area. Aquifers of the region are represented by parent basalt rocks of the deccan trap with low primary porosity and hydraulic conductivity (Kulkarni et al., 2000; Mohapatra, 2013). The storage of these aquifers is primarily limited to water-bearing zones mostly confined to upper shallow (15–30 m) weathered and fractured zones of hard rock (Kulkarni et al., 2000; Mohapatra, 2013). Groundwater from the top 15–30 m of weathered upper parts is tapped by open large diameter (4–8 m) dug wells usually 15–30 m deep (Kulkarni et al., 2000; Mohapatra, 2013). The groundwater availability in upper weathered zone remains limited in the post-monsoon season and is mostly depleted by the end of the year because of the limited extent and storage of aquifers (Foster, 2012; Alam et al., 2022c) thus limiting cultivated area in post monsoon seasons (Alam et al., 2022c). Groundwater availability in deeper aquifers is limited and dependent on nature and the degree of vertical and horizontal joints and fractures (Kulkarni et al., 2000; Foster, 2012). The deeper aquifer is tapped by deep (~100–300 m) borewells.

2.1 Agricultural water management interventions in the region

The vulnerability of the agriculture sector is high in India with large part of the country under arid and semi-arid climate and half of the cropped area being rainfed (Alam et al., 2021; Sikka et al., 2022). Saurashtra region with low and highly variable rainfall faces frequent droughts and associated production losses (Alam et al., 2022c).

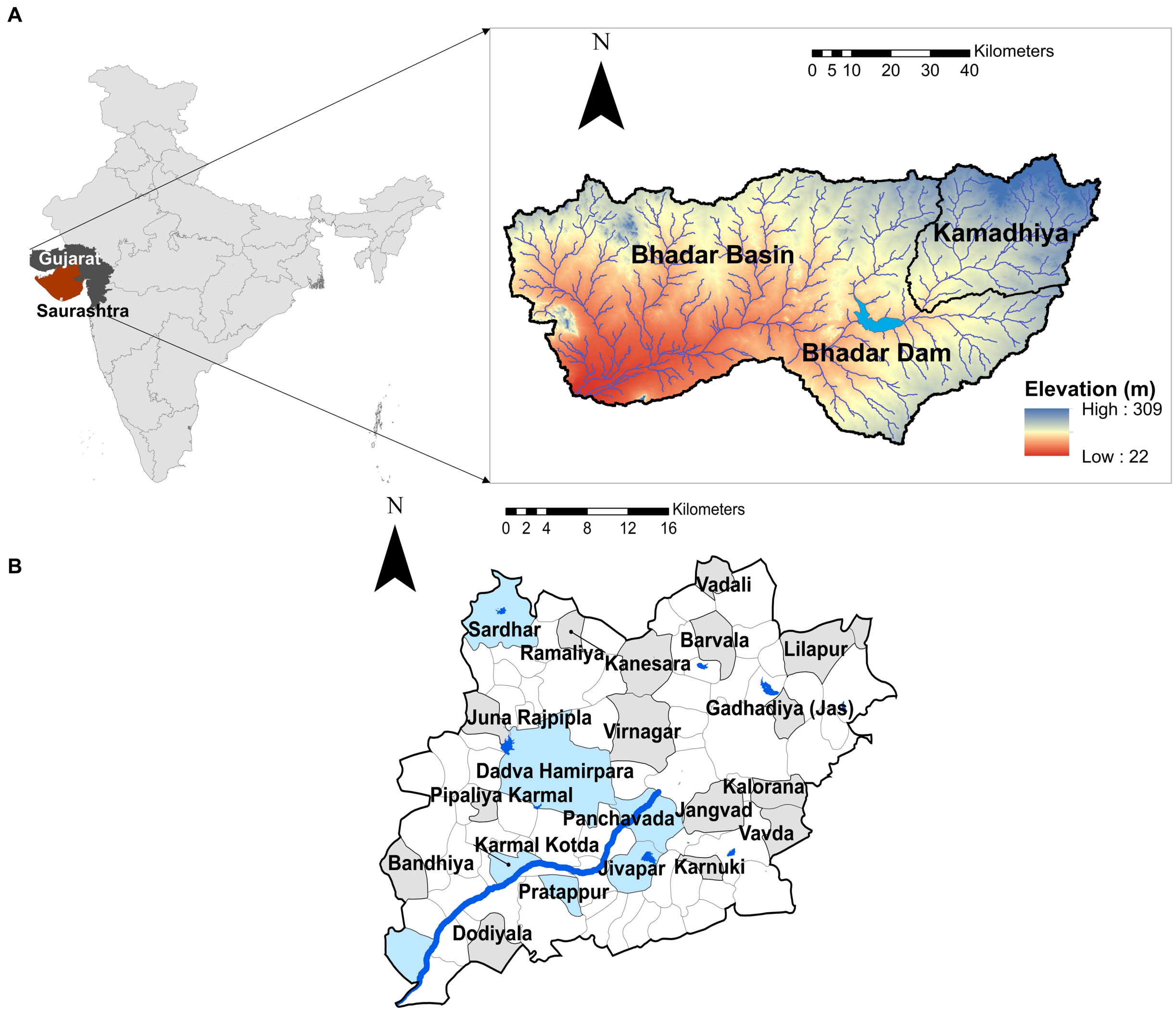

FIGURE 1
(A) Location of Kamdhiya catchment, Bhadar basin, Saurashtra region and Gujarat state in India. **(B)** Sampled villages for household survey in Kamadhiya catchment. In light blue color are the villages that lie downstream of dams (shown in dark blue) or near to the main stem of the river (stream order > = 4).

Governmental and non-governmental organizations have been promoting a range of interventions in the area to mitigate the impact of short and unpredictable monsoons. The key interventions in the region include supply augmentation through check dams, which are community water harvesting structures largely built on common land through state resources (Alam et al., 2022a) and increasing the efficiency of water use through drip irrigation (Namara et al., 2007; GGRC, 2023). The impact of check dams and farmers' perception on check dams has been evaluated earlier (Alam et al., 2022a,c). On other hand, field visits have shown that farmers increasingly are drilling deeper borewells to supplement water from shallow dugwells.

2.1.1 Drip irrigation

Drip irrigation involves applying water and nutrients directly to the crop root zone. Multiple studies have evaluated the benefits of drip irrigation, which includes water savings, yield enhancement, labor savings, efficient fertilizer use, and reduced weed and pest infestation among others (Namara et al., 2007; Palanisami et al., 2011; Singh, 2013; Reddy, 2016). In India, the government has been running capital subsidy programs for more than a decade to increase the adoption of micro-irrigation (including drip), starting with the national mission on micro-irrigation and currently continuing with Pradhan Mantri Krishi Sinchai Yojana (PMKSY—Prime minister Farm Irrigation scheme; DAC&FW, 2017; Nair and Thomas, 2022). Additionally, non-governmental organizations have also invested (funds, knowledge transfer, and training) to increase the uptake of micro-irrigation (Panda, 2003). In the region, Gujarat state government has set up a special purpose vehicle, Gujarat Green Revolution Company (GGRC) limited in 2004–05, to expand the area under micro irrigation in the state (GGRC, 2023). A subsidy of 50% is provided (limited to ~$750/ per hectare) with an additional subsidy of 25% for tribal and scheduled caste farmers (GGRC, 2023).

However, despite being subsidized and with widely reported benefits, multiple studies over time have shown that the adoption of micro-irrigation has remained low (Namara et al., 2007; Palanisami et al., 2011; Nair and Thomas, 2022). The micro-irrigation has been adopted in less than 15% of the potential area in India (Suresh and Samuel, 2020). The question then becomes why?

2.1.2 Borewells

Borewells are narrow, deep wells drilled into the ground using a tube (Steinhübel et al., 2020) to tap deeper aquifers (~100–300 m), in contrast to large diameter shallow (~15–30 m) dug wells. Although dugwells remain the primary source of irrigation, farmers in the study region have increasingly been using borewells to supplement their shallow dugwells. Unlike drip irrigation, borewell drilling in the region is not supported by government subsidies but is being taken up by farmers as a supply augmentation strategy (Kulkarni et al., 2000; Mudrakartha, 2012).

Farmers drill borewells to hedge against production risks associated with low rainfall years, particularly during the dry seasons after the monsoon when the shallow weathered aquifer (15–30 m) in the region dries out (Steinhübel et al., 2020). The drilling of borewells or digging deeper wells as an adaptation strategy in response to droughts or declining groundwater levels has been observed in other parts of the country as well (van Steenbergen, 2006; Mudrakartha, 2007; Jain et al., 2015; Singh et al., 2018; Steinhübel et al., 2020). However, the hard rock aquifers of the region are characterized by low primary porosity and a heterogeneous and low-density fracture network thus leading to high borewell drilling failure rates (Foster, 2012; Robert et al., 2018). Even if borewells are successfully drilled, their yields are low and can only supplement the water supply from dug wells.

3 Methodology

3.1 Household survey

The primary data were collected through a household survey in December 2021. A total of 492 farmers were interviewed across 24 villages in the Kamadhiya catchment (Figure 1). The 24 villages were sampled using a multistage random sampling method. Initially, 24 out of 88 villages within the Kamadhiya catchment were chosen through regular distribution sampling. Thereafter, in each selected village, 20–22 farmers were surveyed using proportionate random sampling. This method involved taking random samples from stratified groups in the same proportion as their representation in the total population (Alam et al., 2022a). The 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 area in the administrative blocks where villages are located. The structured interviews, translated into the local language (Gujarati), lasted approximately 45–50 min and were carried out by a trained team of 10 enumerators native to the region.

3.2 Questionnaire

The structured survey questionnaire consisted of two parts, (1) farmers' socio-economic factors and (2) farmers' perception of drip irrigation and borewells and RANAS related questions regarding the adoption of the irrigation technologies. Farmer socio-economic data included information on farmer's age, gender, number of household members, farming experience, area of land owned, main income sources, livestock, house type, and ownership of material assets (e.g., TV, scooter, car). In addition, data on farmers' cropping practices were also collected.

The questions on drip irrigation and borewells consisted of a mix of informative questions (e.g., cost, subsidy, benefits) and farmers' perceptions about the benefits of each. Questions on RANAS sociopsychological factors (i.e., R-risk, A-attitude, N-norm, A-ability, and S-self-regulation) towards the adoption of drip and bore wells were measured with two to four questions on a five-point Likert scale (Supplementary Table S1).

3.3 Data analysis

A descriptive analysis is carried out to understand farmers' socioeconomic profile in the region and their perception of the benefits and impacts of drip irrigation and borewells. This is followed by a binary logistic regression analysis to understand the main determinants of farmers' behavior toward the adoption of drip irrigation and borewells. Separate logistic regression is carried out for both drip and borewells considering their contrasting roles and assuming that adoption of one technology does not necessarily influence adoption of the other. This is supported by field observations indicating farmers consider them as individual technologies catering to separate goals.

Binary logistic regression is a statistical method that estimates the probability of one of two possible outcomes, based on a set of predictor variables and is appropriate when the dependent variable has only two outcomes (e.g., such as yes/no or adopters/non-adopters; Tranmer and Elliot, 2008; Harris, 2021). To account for variations in village size, sampling weights (farmers interviewed in each village divided by the village population) were derived and used in the analysis. The effects (coefficients) estimated by a logistic regression are interpreted as changes in the log-odds of the outcome variable for one-unit change in the predictor variables, with other variables held constant. A positive and significant coefficient indicates an increased likelihood of the outcome, while a negative and significant coefficient indicates a decreased likelihood. The magnitude of the coefficient indicates the strength of the association (Tranmer and Elliot, 2008; Harris, 2021). Binary logistic regression has been used widely across fields and in a range of studies to evaluate the adoption of water management technologies (Namara et al., 2007; Singh, 2013; Patil et al., 2019; Raut et al., 2021; Yifru and Miheretu, 2022).

3.4 Definition and selection of variables

The dependent variable was whether a farmer has adopted drip irrigation (or borewells) or not. A value of 1 was assigned to all the farmers who use drip irrigation and 0 to those who use other irrigation methods. The use of sprinkler irrigation was negligible in the area. For borewells, a value of 1 was assigned to all the farmers who have installed a borewell in addition to dugwell(s) and 0 to those who only have dugwells. The farmers that only had borewells as their primary source of irrigation were excluded from the logistic regression of borewell adoption.

The RANAS model factors (risk, Attitude, Norms, Abilities, and Self-regulation) represent different multiple socio-psychological factors of farmers. Risk factors represent a person's understanding and awareness of the health risk; Attitude factors represent a person's positive or negative stance towards a behavior; Norm factors represent the perceived social pressure towards a behavior; Ability factors represent a person's confidence in her or his ability to practice a behavior and self-regulation factors represent a person's attempts to plan and self-monitor behavior and to manage conflicting goals and distracting cues (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 (Supplementary Table S1).

For RANAS factors measured with three or more questions (measuring common latent variables) principal component analysis (PCA) was used to address multicollinearity (Daniel et al., 2020). Table 1 gives the results of the PCA and redefined psychological factors for all RANAS factors measured with three or more questions. For instance, the three questions on perceived ability (financial, knowledge, operate) to adopt drip irrigation were renamed as "ability" since they all loaded on the first principal component (Table 1). Likewise, the five questions related to risk were renamed as perceived vulnerability and severity, which loaded on the first two principal components, separating risk and impact factors (Table 1). Table 2 lists the final RANAS factors retained for the binary logistic regression.

The selection of explanatory variables, in addition to RANAS psychological variables, was done based on previous studies that have shown that the adoption of practices is influenced by a range of socio-economic factors including farmers' economic, social, and demographic factors (Namara et al., 2007; Nair and Thomas, 2022; Yifru and Miheretu, 2022). This included farmer owned land, age, farming experience, education, income from agriculture and wealth (defined by ownership of assets). Additionally, based on field visit observations, number of livestock, distance from check dam and proximity to river or dams (Shown in Figure 1B) were identified as important factors and were added. The location of the administrative block in which farmers are located was added to account for other unobserved factors. A multi-collinearity analysis was carried out among the socioeconomic variables and any variables with a high degree of correlations (threshold of 0.6) were removed. Final socioeconomic and biophysical variables retained for the binary logistic regression are presented in Table 2.

4 Results and discussion

4.1 Descriptive statistics

The average landholding in the catchment was reported to be 2.9 hectares (median = 2.0 hectares). Small farmers (1–2 ha) represented the highest share of sample farmers (31.7%) followed by medium (2–4 ha; 27.8%) and large (> 4 ha; 23.4%) and marginal (< 1 ha; 17.5%) farmers. More than 60% of farmers were above the age of 40 and had 8 years or less of schooling. Agricultural income from crop production (99.2% of farmers) and livestock rearing (71.7%) were the main sources of income. Further description of socioeconomic statistics can be found in Supplementary Table S2.

Table 3 gives a summary of agriculture and irrigation characteristics in the region. Cotton and groundnut are the main Kharif crops (~98% area) covering 44 and 54% of the Kharif cultivated area, respectively. Rabi cultivated area is limited (~46% of Kharif cultivated area), with chickpea (49%), cumin (24%), and wheat (15%) being the main crops. Cultivation is negligible in the area from March to May. Overall ~97% of the farmers reported having access to irrigation, with groundwater (~96%) being the main source of irrigation.

For the Kharif crops, ~80% of farmers indicated that they irrigate always (every year) whereas ~10% indicated that irrigation is needed only in dry years. On the other hand, almost all farmers indicated that they irrigate their crop always (every year) in the post-monsoon Rabi season reflecting the lack of rainfall. About two-thirds of the farmers indicated that their irrigation source is not sufficient (not sufficient or only a little sufficient) in dry years, which shows limited groundwater storage in the region. Regarding the irrigation schedule, most farmers indicated they irrigated when they felt the need.

4.2 Adoption of drip irrigation and borewells

4.2.1 Drip irrigation

Overall adoption of drip irrigation is low in the catchment with only 16.5% of the farmers using drip irrigation systems. The use of drip irrigation is mainly for the cotton crop (10.4%) followed by small areas under groundnut cultivation (2.7%; Table 2). This is despite the subsidy program by the government with farmers reporting an average of ~50% subsidy for drip irrigation systems. Also, both cotton and groundnut, dominating the cropping area are cash crops and are suitable for drip irrigation. Studies have shown that adopting drip irrigation has technical and economic benefits, including water savings and increased physical and economic water productivity for both crops (Namara et al., 2007; Singh, 2013). For Rabi crops, the use of drip irrigation remains negligible. Micro irrigation remains less suitable for cereals and pulses (Namara et al., 2007; Singh, 2013), which could explain negligible use in the Rabi season. The main irrigation method reported was conventional flood irrigation for all crops except groundnut where both furrow and flood irrigation are used (Table 3).

The statistical tests (*t*-test and chi-square; Table 2) showed that adopters were significantly ($p < 0.05$) wealthier and earned a higher percentage of their income from agriculture. Similarly, adopters' have higher landholdings, with significantly more large farmers being adopters and significantly fewer marginal farmers being non-adopters. With respect to the psychological factors, adopters show significantly higher ability, positive belief about the utility of the drip irrigation technology, and societal norms towards drip irrigation systems.

4.2.2 Borewells

In the catchment, 57.3, 12.8, and 24.6% of farmers reported owning only a dugwell, a borewell and a borewell in addition to a dug well, respectively. The latter group of farmers who own a borewell in addition to a dugwell (24.6% of farmers) are referred to as adopters and those who own only a dugwell are referred to as non-adopters.

The average depth of borewells was reported to be ~115 meters (ranging from 45 to 300 meters) against the average depth of ~20 m for dugwells. This shows that borewells are accessing deeper groundwater. The average age of borewells is ~12 years against

TABLE 1 Principal component analysis (PCA) on RANAS factor question for Drip and borewell.

RANAS factors	Question	Principal Component-1 (Loading)	Principal Component-2 (Loading)	Renamed variable
Drip[a]				
Risk[b]	How many drought/dry years have been there in last 10 years?	0.785		70% of the data variance is explained by the first two principal components (PC). Questions related to risk load highly on PC-1 and related to impact load highly PC-2. Thus PC-1 and PC-2 resulting from the PCA was used to represent "Risk (Perceived vulnerability)" and "Risk (Perceived severity)," respectively.
	How high is the risk of your groundwater wells going dry in next 5 years?	0.791		
	How high is the risk of drought in coming 5 years?	0.847		
	How severe will be the impact of drought on your crop production?		0.846	
	How much GW decline will impact your crop production?		0.827	
Ability	How confident are you in your financial capability to afford the drip irrigation system? [w/o subsidy]	0.769		70% of the data variance is explained by the first PC-1 and all questions loading highly on this. Thus PC-1 resulting from the PCA was used to represent "Ability (drip irrigation)."
	How confident are you in your capacity/knowledge to install the drip irrigation system?	0.879		
	How confident you are in your capability to operate and maintain the drip irrigation system?	0.849		
Norm	What proportion of people in your village have a drip irrigation system?	0.830		85% of the data variance is explained by the first two principal components (PC). Questions related to proportion of people and their opinion load highly on PC-1 and related to NGOs/government official opinions load highly PC-2. Thus PC-1 and PC-2 resulting from the PCA were used to represent "Society norm" and "NGO norm," respectively.
	Most people whose opinion I value think having drip irrigation is good?	0.739		
	How important are NGOs/government official opinions to you?		0.976	
Attitude	How beneficial drip irrigation is for crop production?	0.880		85% of the data variance is explained by the first two principal components (PC). Questions related to benefit and reliability load highly on PC-1 and related to time load highly PC-2. Thus PC-1 and PC-2 resulting from the PCA were used to represent "Attitude (Reliability and benefits)" and "Attitude (Time)," respectively.
	How reliable is applying irrigation with drip irrigation?	0.882		
	How time consuming is to get a drip irrigation set up?		0.995	
Borewell[c]				
Norm	What proportion of people in your village have a borewell?	0.858		85% of the data variance is explained by the first two principal components (PC). Questions related to proportion of people and their opinion load highly on PC-1 and related to NGOs/government official opinions load highly PC-2. Thus PC-1 and PC-2 resulting from the PCA were used to represent "Society norm" and "NGO norm," respectively.
	Most people whose opinion I value think having borewell is good?	0.808		
	How important are NGOs/government official opinions to you?		0.976	
Attitude	How beneficial borewell is for crop production?	0.880		85% of the data variance is explained by the first two principal components (PC). Questions related to benefit and reliability load highly on PC-1 and related to time load highly PC-2. Thus PC-1 and PC-2 resulting from the PCA were used to represent "Attitude (Reliability and benefits)" and "Attitude (Time)," respectively.
	How reliable is irrigation water supply from borewell?	0.882		
	How time consuming is to install a borewell?		0.995	

[a] For drip, self-regulation was measured with one questions only (Table S1) so no PCA done.

[b] Risk questions were common for both drip and borewell.

[c] For borewell, ability and self-regulation were measured with two questions (Supplementary Table S1) only so no PCA done and all questions were used in the analysis. Risk questions were same as drip.

TABLE 2 Description and summary statistics (mean and percentage) of the variables used in the binary logistics model.

Variable	Description	Adopters	Non-adopters	Adopters	Non-adopters
		Drip Irrigation		Borewell	
Dependent variable					
Drip or borewell adoption	Have adopted drip irrigation/borewell (count)	79	399	122	286
Psychological variables (RANAS)					
Risk (Perceived vulnerability)*	Farmers' perception of risk (drought, groundwater)? (mean)	1.78[s]	2.03[s]	1.79	2.04
Risk (Perceived severity)*	Impact of drought and groundwater decline on crop production? (mean)	2.92	2.83	2.82	2.88
Attitude (Reliability and benefits)*	How beneficial and reliable drip irrigation/borewell is for crop production? (mean)	2.94[s]	2.28[s]	2.24[s]	1.75[s]
Attitude (Time)	How time-consuming is it to get a drip irrigation/borewell set up? (mean)	2.19	1.65	2.74[s]	1.27[s]
Ability (drip irrigation)*	How confident are you in your financial and knowledge to own, operate and maintain the drip irrigation? (mean)	2.18[s]	1.47[s]	-	-
Financial ability (borewell)	How confident are/were you in your financial capability to afford the drilling of a BW?	-	-	1.28	1.07
Technical ability (borewell)	How confident are/were you in your capacity/knowledge to install a BW?	-	-	1.75	1.49
Societal norm*	What proportion of people in your village have a drip irrigation/borewell and people whose opinion you value think having drip irrigation/borewell is good? (mean)	2.03[s]	1.56[s]	1.99[s]	2.18[s]
NGOs Norm	How important are NGOs/government official opinions to you? (mean)	1.64	1.47	1.58	1.48
Drip Self-regulation (attention to water application)	How much do you pay attention to how much water you use for irrigation? (mean)	3.43	2.97	-	-
BW Self-regulation (Action planning 2)	Do you have the plan to acquire the required personnel and material it takes to drill a borewell? (mean)[p]	-	-	1.89	1.05
BW Self-regulation (Action planning 2)	Do you have a plan if your borewell does not yield water or stop giving water? [p] (mean)	-	-	1.30	1.15
Socio-economic					
Land[a] (Total area cultivated by the farmer; %)	Marginal (%)	6.3[s]	17.8[s]	8.3	15.6
	Small (%)	24.1	33.1	28.9	31.6
	Medium (%)	26.6	28.8	29.8	28.7
	Large (%)	43.0[s]	20.3[s]	33.1	24.1
Experience	Years of experience in farming (mean)	29.8	26.7	27.9	26.88
Education[a] (Year of education of farmers)	No education (%)	17.7	23.8	24.8	22.3
	Primary (%)	36.7	31.3	29.8	33.3
	Secondary (%)	44.3	41.6	40.5	41.8
	Higher (%)	1.3	3.3	5.0	2.5
HH members	Number of Household members (mean)	5.2	5.5	5.04	5.65
Income from Agriculture	Percent of income coming from Agriculture (mean)	68.2[s]	60.5[s]	65.1	62.62
Wealth[b]	Score on things owned (gas connection, TV, fridge, 2-wheeler, AC, and Car; mean)	9.7[s]	8.4[s]	9.25[s]	8.55[s]
Livestock numbers	Number of livestock owned by the farmer (mean)	2.17[s]	2.82[s]	3.38	2.45
Biophysical variables					
CD distance	Distance from nearest check dam in meters (mean)	1317.5	1314.4	1449.12	1311.68

(Continued)

TABLE 2 (Continued)

Variable	Description	Adopters	Non-adopters	Adopters	Non-adopters
		Drip Irrigation		Borewell	
Block[a]	Gondal (%)	26.6	21.3	28.9	19.5
	Babra (%)	5.1[s]	14.0[s]	13.2	9.2
	Jasdan (%)	51.9	48.1	43.8	51.4
	Kotda (%)	5.1	9.0	9.1	8.5
	Rajkot (%)	7.6	3.5	4.1	5.0
	Chotila (%)	3.8	4.0	0.8[s]	6.4[s]

T-test and chi-square tests are done to assess if the differences between adopters and non-adopters are significant. Superscript [s] represents a significant difference ($p < 0.05$) of mean or proportion between adopters and non-adopters.

*Taking average of individual RANAS questions (Supplementary Table S1) before PCA.

[a] Dummy variable.

[b] Wealth was derived as score from ownership of material assets. Wealth = 1*gas connection + 2*fridge + 2*tv + 2*two wheeler + 3*ac + 4*car + 1*kuccha house + 2*semi-pucca + 3*pucca.

TABLE 3 Agriculture and Irrigation characteristics for the main crops in the region.

		Kharif season (Jun – Oct)		Rabi (Nov – Feb)		
		Cotton	Groundnut	Chickpea	Cumin	Wheat
Percentage of season area	Area (%)	44.1	53.9	49.2	24.3	14.9
Irrigation (%)	Always	84	80.0	93.5	100	100
	Never	2	1.4	0.00	0	0
	Only in a dry year	11	13.7	3.7	0	0
	In dry spell	3	4.8	2.8	0	0
Irrigation source sufficiency in dry year (%)	Not	24.5	23.5	19.9	22.5	19.2
	a little	40.1	40.1	41.7	42.3	51.9
	sufficient	29.9	29.9	31.0	27.0	24.0
	quite	5.1	5.9	5.6	5.4	4.8
	very sufficient	0.3	0.98	1.9	2.7	0.0
Irrigation method (%)	Flood	8.0	6.7	6.40	7.21	7.4
	Furrow	16.7	46.9	13.8	11.7	14.7
	Drip	10.4	2.7	0.5	0.9	0.0
	Sprinkler	0.3	3.0	1.5	0.0	0.0
	Bed	64.4	40.6	77.8	80.2	77.9
Irrigation schedule (%)	no plan	6.7	7.3	10.2	9.0	6.7
	crop calendar	0	0	0.0	0.0	0.0
	moisture probe	3.8	4.4	8.8	4.5	4.8
	examine soil visual	5.4	5.6	5.6	5.4	2.9
	irrigate when need	82.5	81.9	68.1	74.8	78.8
	irrigate every day	1.6	0.7	7.4	6.3	6.7

~25 years for dugwells, which shows that the drilling of borewells has started more recently. The drilling of borewells is capital intensive. The average cost of drilling a borewell and associated pump (~6 HP) was reported to be ~120,000 INR (~1,450 USD). The drilling of borewells was also associated with high failure rates. The farmers who owned a borewell reported drilling on average 2.3 bore wells (range 1–12) to get a successful bore. This was also reflected in farmers' reported reason for not owing a borewell, with 42% saying that it is too expensive and 35% saying it is too difficult to drill one. Additionally, 10% of farmers reported trying for one but not having success.

The main benefits of borewells as reported by farmers, both adopters and non-adopters, was the protection against drought (86%), followed by an increase in the Rabi (post-monsoon) cropping area (53.3%). This corroborates observations from the field studies that demonstrate that borewells are primarily adoption measures against low water availability in the dry or post-monsoon season (Birkenholtz, 2009). This is also reflected in the crop data reported by the farmers. On average, borewell owners reported cultivating 53.7% of their Kharif area in the Rabi season as opposed to 40.9% by non-adopters.

The statistical tests (*t*-test and chi-square) showed that adopters were significantly wealthier ($p < 0.05$). However, no significant difference in landholdings between the adopters and non-adopters was found. Also, the adopters have a higher perceived ability and more positive belief toward borewells than non-adopters.

4.3 Factors influencing the adoption

Table 4 presents the results of binary logistic regression for drip irrigation and borewells, with two regression models implemented for each technology. Model 1 included both socio-economic and

TABLE 4 Results of binary logistic regression of farmer's decision to adopt drip irrigation and borewells.

	Drip Irrigation				Borewell			
	Model 1		Model 2		Model 1		Model 2	
	Estimate	Odds ratio[a]	Estimate	Odds ratio	Estimate	Odds ratio	Estimate	Odds ratio
(Intercept)	−5.26***	0.01	−4.47***	0.01	−3.09***	0.05	−2.6**	0.07
Experience	0.04**	1.04	0.01	1.01	0.01	1.01	0.01	1.01
Higher education[#]	−2.49**	0.08	−1.42	0.24	1.2	3.32	0.59	1.80
Primary education[#]	0.28	1.32	0.29	1.34	−0.73*	0.48	−0.71*	0.49
Secondary education[#]	−0.51	0.60	−0.26	0.77	−0.49	0.61	−0.56	0.57
Income from farming	0.01	1.01	0.01	1.01	−0.01	0.99	0	1.00
Household members	−0.08	0.92	−0.09	0.91	−0.09	0.91	−0.12**	0.89
Livestock count	−0.08	0.92	−0.07	0.93	0.09**	1.09	0.1**	1.11
Distance from Check dam	0	1.00	0	1.00	0**	1.00	0	1.00
Proximity to dam and river[#]	−1.64***	0.19	−1.48***	0.23	1.23**	3.42	0.93**	2.53
Wealth	0.15**	1.16	0.24***	1.27	0.02	1.02	0.09	1.09
Small farmer[#]	0.55	1.73	0.88	2.41	1.24**	3.46	0.83*	2.29
Medium farmer[#]	0.19	1.21	1.01	2.75	1.06*	2.89	0.97*	2.64
Large farmer[#]	1.07	2.92	1.52**	4.57	1.54***	4.66	1.21**	3.35
Babra block[#]	−0.96	0.38	−1.21*	0.30	0.12	1.13	0.81	2.25
Jasdan block[#]	−0.22	0.80	−0.25	0.78	−0.33	0.72	−0.01	0.99
Kotda block[#]	−1.75**	0.17	−1.29*	0.28	0.41	1.51	0.4	1.49
Rajkot block[#]	1.29*	3.63	1.4**	4.06	−1.33**	0.26	−0.84	0.43
Chotila block[#]	−1	0.37	−0.73	0.48	−1.48	0.23	−1.86*	0.16
Gondal block[#]		-	-	-			-	-
Ability 1	0.81***	2.25	-	-	−0.08	0.92	-	-
Ability 2			-	-	−0.06	0.94	-	-
Perceived risk: Vulnerability	−0.75***	0.47	-	-	0.02	1.02	-	-
Perceived risk: Severity	−0.48*	0.62	-	-	0.04	1.04	-	-
Attitude (benefits, reliability)	0.73***	2.08	-	-	0.77***	2.16	-	-
Attitude (time)	0.33	1.39	-	-	0.01	1.01	-	-
Society norm	0.29	1.34	-	-	0.45**	1.57	-	-
NGO norm	0.19	1.21	-	-	0.05	1.05	-	-
BW Self-regulation (Action planning 1)	-	-	-	-	0.46***	1.58	-	-
BW Self-regulation (Action planning 1)	-	-	-	-	0.33**	1.39	-	-
Drip Self-regulation (attention to water application)	0.29	1.34	-	-	-	-	-	-
Psedu-R2	0.307		0.116		0.214		0.070	
Accuracy	88.4%		84.3%		76.9%		69.6%	
AUC	87.1		75.9		78.6		69.7	

***, **, *Significant at <= 1, 5, and 10% probability level, respectively. All VIF < 10.[a]Odds ration = exp(estimate).
[#]Dummy variable.

psychological factors, while Model 2 considered only socio-economic factors. The results revealed that incorporating psychological factors improved the model's explanatory power by almost threefold for adopting both drip and borewells.

For drip irrigation, Model 1 yielded a pseudo-R^2 of 0.31, with an overall accuracy of 88.4% and an area under the ROC Curve (AUC) of 87.1%, indicating satisfactory model performance. In contrast, Model 2 (only socio-economic factors) produced a lower pseudo-R^2 of 0.12, with corresponding reductions in overall accuracy (84.2%) and AUC (75.9%). Similarly, for borewells, Model 1 generated a pseudo-R^2 of 0.21, with an overall accuracy of 76.9% and an AUC of 78.9%. Model 2 had a lower pseudo-R^2 of 0.07, with corresponding reductions in overall accuracy (69.6%) and AUC (69.7%).

These findings underscore the significance of psychological factors in explaining farmers' adoption decisions, as they influence their attitudes, beliefs, perceptions, and motivations towards new technologies or practices. While previous studies on adoption have often overlooked the role of psychological factors (Namara et al., 2007; Nair and Thomas, 2022), our results demonstrate that considering these factors can facilitate a better understanding of farmers' adoption decisions. This can help extension workers, researchers, and policymakers develop effective strategies to promote the adoption of new technologies among farmers. In the following section, we have discussed results from the model 1 which combines both socio-economic and psychological factors.

4.3.1 Land size and wealth

Earlier studies have widely reported that larger or wealthier farmers are more likely to adopt both drip irrigation and bore well technologies, as both require significant capital investments (Namara et al., 2007; Singh et al., 2018; Patil et al., 2019; Nair and Thomas, 2022). This is reflected in results which show that small, medium, and large farmers are 246% ([odds ratio − 1]*100), 189% (at 10% significance level) and 366% more likely to adopt borewells as compared to marginal farmers, respectively. The influence of land size is not visible for drip irrigation. However, wealth (an indicator of capital) shows significant positive but small (~16%) positive influence on drip irrigation adoption. Additionally, the ownership of more livestock significantly increases the adoption of borewells by 9% and could be explained by the need to fulfill the water needs of livestock.

4.3.2 Proximity to water (river, dam, and check dams)

The impact of proximity to water sources, such as the main river and dam, on the adoption of drip and borewell irrigation is significant, but in opposite directions. In contrast to a 242% increase in the adoption of borewells, the likelihood of adopting drip irrigation decreases by approximately 81% in villages with proximity to rivers or dams. This could be due to the increased recharge in downstream villages near rivers and dams, which increases the success rate of borewell drilling and the availability of groundwater, prompting more farmers to adopt borewell irrigation. However, this also suggests that the increased availability of water (absence of water scarcity) may make farmers less inclined to adopt drip irrigation. This observation reflects the presence of supply–demand feedback, where increased water supply leads to an increase in demand (Scott et al., 2014; Di Baldassarre et al., 2018) and less adoption of demand management measures. The impact of check dams' proximity on adoption is negligible, indicating their limited and short-lived storage (Alam et al., 2022a).

4.3.3 Perceived ability

A strong perception of one's ability to practice (operate, maintain, and financially afford) drip irrigation translates to a 125% greater likelihood of its adoption. With lack of technical knowledge and support after adoption along with high cost of maintenance (e.g., replacement of parts) being major constraints for adoption (Nair and Thomas, 2022), it is natural that those who have more confidence in their ability to do so adopt more. Low adoption in the region is also due to farmers' perceived financial inability to afford drip irrigation systems, as reflected in the low score (mean score = 1.28) on the perceived financial ability data. In comparison, farmers reported higher capacity to install (mean score = 1.65) and operate and maintain (mean score = 1.89) the systems.

Farmers reported the average cost of drip installation to be ~65,000 INR (~790 USD) /hectare and after an average subsidy of 50%, this would translate to a farmer share of ~32,500 INR (~395USD) /hectare. This upfront investment in combination with a lack of belief in benefits may be limiting farmers' adoption of drip irrigation systems. However, it could also be due to institutional and operational issues in the subsidy programs (e.g., delay in subsidy disbursement, the requirement to pay full cost upfront, and cumbersome paperwork) that have been highlighted by several studies (Chandran Madhava and Surendran, 2016; Malik et al., 2018; Misquitta and Birkenholtz, 2021; Nair and Thomas, 2022). While the Gujarat state special purpose vehicle, Gujarat Green Revolution Company (GGRC), to increase adoption has been highlighted as a relatively successful model with good institutional mechanism (Pullabhotla et al., 2012), the case of institutional issues needs to be further investigated.

Other than financial ability, limited capacity to operate and maintain drip irrigation has been highlighted as a key barrier to adoption (Palanisami et al., 2011; Cremades et al., 2015; Nair and Thomas, 2022). Thus, farmers who have higher perception of their capability to operate and maintain also adopt more (Table 4). For drip irrigation, the lack of capacity has been related with a lack of extension services and post-adoption support with frequent issues of clogging of filters and drippers in drip irrigation systems (Palanisami et al., 2011; Nair and Thomas, 2022). Field visits have shown that issues associated with clogging along with challenges for storing drip systems due to damage caused by rodents that gnaw the drip irrigation tubings creating holes were reiterated by farmers and hinders adoption.

In contrast to drip irrigation, perceived ability (financial and knowledge to install) did not significantly influence the adoption of borewells. This could be as with high uncertainty of successful borewell drilling, higher perceived financial and capacity/knowledge to install a borewell does not necessarily lead to higher adoption. This is similar to findings from Ethiopia where a reduction in ambiguities related to well drilling was found to be one of the main factors influencing the adoption of groundwater irrigation (Balasubramanya et al., 2023).

4.3.4 Attitude towards technology

Results show that for drip irrigation and borewells, positive belief about the reliability and benefits of the technology translates to a 108 and 116% increase in the likelihood of adoption, respectively. This corroborates the observation from earlier studies that have also shown the importance of positive belief in increasing the adoption of micro-irrigation in India (Hatch et al., 2022), China (Wang et al., 2020) and Iran (Nejadrezaei et al., 2018). Nair and Thomas (2022), based on their review of micro-irrigation adoption in India, also observed that awareness regarding the benefits of drip irrigation is central to increasing adoption. Similarly, Reddy (2016), evaluating the Andhra Pradesh Micro Irrigation Project program, also found that awareness activities (television and radio programs, live demonstrations) played a key role in the success of the program. Interestingly, higher education negatively influences the adoption of drip irrigation (Table 4) showing that more years of education does not necessarily lead to more awareness about drip irrigation benefits and higher adoption.

4.3.5 Perceived risk and impact

The results show that for drip irrigation, interestingly, an increase in perceived vulnerability and associated impact severity translates to a 53 and 38% decrease (at 10% significance level) in the likelihood of drip irrigation adoption, respectively. Whereas for borewells, the impact of perception of risk and vulnerability on adoption is not significant. Theoretically, both drip irrigation and borewells may act as risk-reducing strategies under conditions of water scarcity by using water more efficiently and augmenting the supply of water from deeper aquifers, respectively. Thus, intuition may suggest that an increase in perceived vulnerability and associated impacts should be associated with an increase in adoption of both. This has been observed in other studies where farmers choose to adopt the new technology/practices (e.g., crop insurance, efficient irrigation) to hedge/reduce the risk (Koundouri et al., 2006; Saqib et al., 2016).

The contrasting impact of perceived risk and vulnerability on the adoption of drip irrigation and borewell technologies reveals the differing nature of these technologies as perceived by farmers. Field observations indicate that farmers do not see drip irrigation as a solution for water scarcity as in times of water scarcity (as in dry years), drip irrigation is considered redundant (without any irrigation water). Thus, while the perceived threat of water scarcity is higher, adoption of drip irrigation remains low due to farmers' perception of the technology's benefits and costs. This suggests a lack of awareness about the benefits of drip irrigation as a risk-reducing strategy, as well as a perceived imbalance between the cost of adoption and the benefits it provides. Additionally, frequent climate threats, such as drought in the region, can lead to losses in crop yields and revenue, reducing farmers' financial capacity to invest in risk-reducing strategies (Alam et al., 2022c).

Additionally, the common pool nature of groundwater where the same aquifer is accessed by multiple users creates challenges for adoption of demand management strategies such as drip irrigation (Gardner et al., 1990; Asprilla-Echeverria, 2021). This is because saving water in one's well using drip irrigation does not necessarily translate to actual savings for the farmer if other farmers continue to abstract without drip irrigation.

4.3.6 Societal norm

The societal norms, perceived social pressure towards a behavior, have a positive influence on farmers' adoption behavior by affecting their perception of confidence, the benefits of adoption, norm conformity, learning, and perceived risk reduction (Daxini et al., 2019; Streletskaya et al., 2020; Qiu et al., 2021; Hatch et al., 2022). The results suggest that an increase in societal norms leads to a 57% increase in the likelihood of adopting borewell irrigation but has no significant impact on drip irrigation adoption. The positive impact of societal norms on borewell adoption may be due to farmers' perception of the success of borewells in nearby farms. However, the study was not able to determine why the same impact does not hold for drip irrigation adoption.

In addition, the study found that the opinions of government and NGOs do not significantly influence the adoption of drip or borewell irrigation. This may be because most farmers rely on neighboring farmers (71.8%), agro-dealers and private companies (56.9%), and lead farmers (39.1%) for information, while less than a quarter of farmers reported government or NGOs as their source of information. This finding highlights the importance of considering these channels while designing awareness and extension activities for promoting technology adoption.

4.3.7 Other factors

Action planning significantly increases borewell adoption by farmers. Access to information on external factors such as drilling contractors, engineers, and technicians is a key determinant of adoption. However, the observed association may be explained by reverse causality, as borewell owners are more knowledgeable about the necessary resources for drilling (Daniel et al., 2020). For drip irrigation, farming experience shows a slightly positive (4% increase for each unit increase in farming experience) impact on adoption. Household size and income from farming did not have any influence on the adoption of both drip irrigation and borewell irrigation.

4.4 Discussion and recommendations

Our findings show that although subsidies (50–70%) are available for drip irrigation systems, adoption rates remain low (approximately 16% adoption rate). In contrast, the adoption rate for borewells, which require more capital investment and have no subsidies, is higher (approximately 24.5%). This suggests that farmers prioritize augmenting their water supply and view borewells as a more effective means of mitigating water scarcity or intensifying cultivation. This trend is consistent with observations from Patil et al. (2019) in another water-stressed area of Southern India, where the uptake of water-saving technologies was low, and farmers chose water-intensive crops and unregulated pumping, which exacerbates water stress.

The results indicate that the availability of water (proximity to dam and river) and higher perception of risk negatively affect the adoption of drip irrigation. This reflects that farmers may not necessarily perceive drip technology as a risk-reducing strategy, thereby hindering adoption. Furthermore, limited financial and technical capacity is another obstacle to adoption. Thus, a multi-pronged approach is necessary to build farmers' capacity to adopt drip irrigation (including alternative financial mechanisms and capacity building) and to raise awareness of its benefits.

Although subsidies have been shown to positive impact adoption (Heumesser et al., 2012; Cremades et al., 2015), our results indicate that in the region, subsidies alone are not enough to promote the adoption of drip irrigation. Alternative financial mechanisms may be required, such as increasing subsidies or providing low-interest or interest-free loans to cover the unsubsidized cost (Palanisami et al., 2011; Nair and Thomas, 2022). An example of this is the Aga Khan Rural Support Programme (AKSRP) in the study region which provided added subsidies and interest-free loans (with delayed repayment) to cover the unsubsidized cost (Panda, 2003). Similarly, other studies have shown the positive impact of easy access and low-interest loans on adoption (Abate et al., 2016; Balasubramanya et al., 2023). For example, Abate et al. (2016) showed in Ethiopia the positive impact of microfinance institutions and member-owned financial cooperatives on the adoption of agricultural technologies by alleviating credit constraints. Alternative financial mechanisms should be accompanied by supporting farmers to easily access the subsidy schemes by making the process faster and more flexible in terms of meeting farmers' requirements (Singh, 2013; Malik et al., 2018).

Additionally, capacity building efforts should prioritize building farmers' confidence in operating and maintaining drip irrigation systems. Research has shown that capacity building for farmers is an effective strategy for technology adoption across various countries and technologies (Arslan et al., 2014; Cremades et al., 2015; Zakaria et al., 2020; Nair and Thomas, 2022). This can be achieved through various means such as training programs, community-based approaches like farmer field schools, access to replacement parts, and post-adoption extension services. The Indian government's operational guidelines for the micro-irrigation subsidy scheme also emphasize the need for capacity building, including organizing training programs and exposure visits (DAC&FW, 2017). In the study region, farmers have expressed concerns about dripper clogging and rodent damage to drip systems, which underscores the need for targeted training on these issues. Capacity building can also involve creating a network of local professionals who can provide on-site training and technical assistance to farmers.

In addition to the aforementioned capacity building efforts, it is essential to provide farmers with information on the benefits of drip irrigation, including increased crop yield and reduced water usage, to reinforce and strengthen positive attitudes and societal norms towards drip irrigation. This is crucial as farmers with higher risk perception are less likely to adopt drip irrigation due to lack of trust in the technology's ability to mitigate risk. Studies in multiple countries have shown that increasing awareness through training, demo farms, and social learning can positively influence adoption rates (Genius et al., 2014; Hunecke et al., 2017; Nejadrezaei et al., 2018; Wang et al., 2020). Ways to achieve this could include increasing access to information through local government institutions, education campaigns, workshops, and field visits. Government guidelines also recommend awareness raising through print and electronic media and publicity campaigns at block/ district/state level (DAC&FW, 2017).

To enhance the influence of extension services such as capacity building and awareness raising, it is important to have a presence and build trust in social, formal, or informal networks (targeting and influencing social norm) such as cooperative organizations and farmers' user groups, rather than focusing solely on individuals (Genius et al., 2014; Hunecke et al., 2017). While the government's official guidelines for promoting micro-irrigation recommend both capacity building and awareness raising (DAC&FW, 2017), low capacity and awareness in the region indicates a need to intensify efforts (Figure 2).

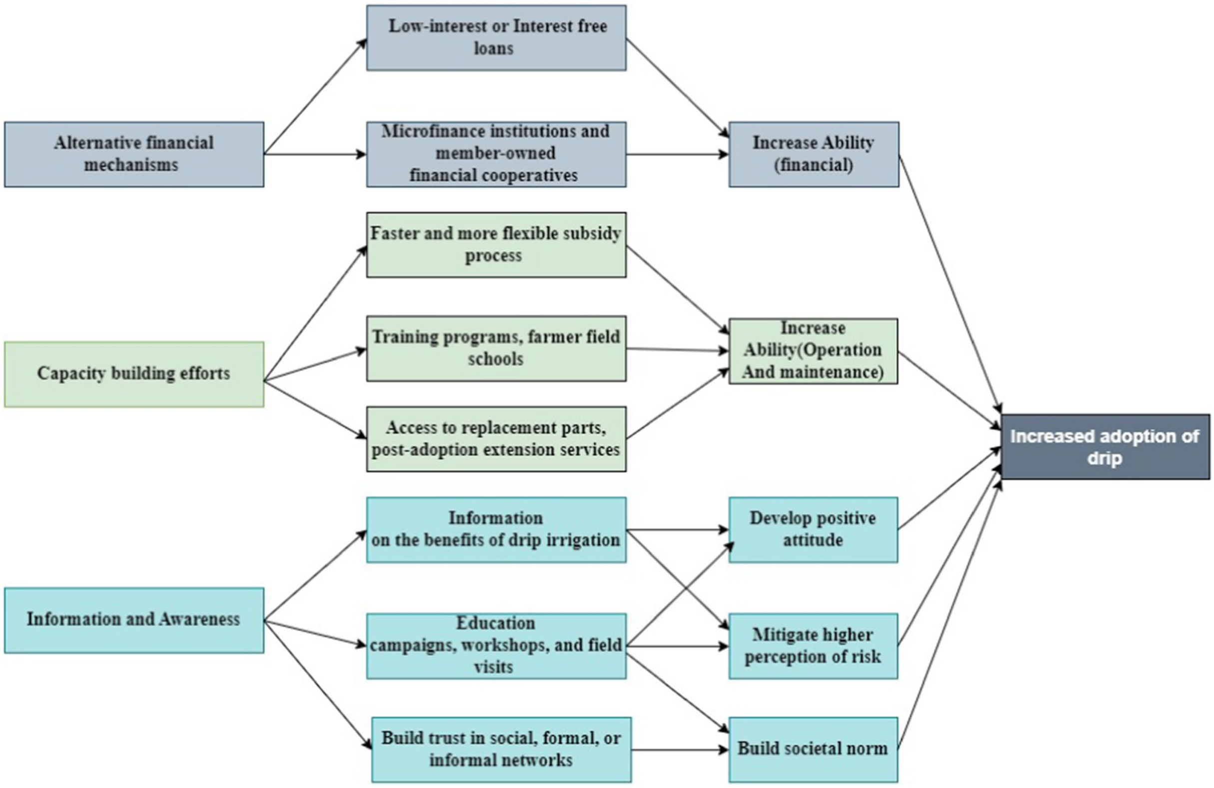

FIGURE 2
Summary of recommendations for increasing adoption of drip irrigation.

However, the increasing adoption of borewells in the region is a cause for concern. While access to borewells may lead to higher availability of water, it comes with social costs. Borewell drilling is capital-intensive and risky in the region, with no guarantee of success. This means that smaller and marginal farmers may not be able to tap the resource, thus exacerbating socioeconomic disparities in the region, as discussed in studies by Patil et al. (2019) in a similar hard rock aquifer area in Southern India and Birkenholtz (2009) in adjoining state of Rajasthan. The financial risks associated with borewells mean that farmers may fall into severe indebtedness with no access to low-interest loans or other safety nets, as observed by Reddy (2012) in a hard rock aquifer region in Southern state of Andhra Pradesh. Our data also show that farmers drill an average of 2.3 borewells (range 1–12) to get a successful borewell. To mitigate the risks and uncertainties associated with borewells, it is essential to provide farmers with information on the underlying hydrogeology, as the hydrogeology in the region is complex.

Additionally, over-extraction of groundwater through borewells can lead to severe depletion and degradation of deeper aquifers. It is not clear whether shallow and deeper aquifers are connected and if connected, tapping deeper aquifers may have a negative influence on shallow water sources. Also, over-extraction of groundwater through borewells can lead to a decline in water levels, making it more difficult and expensive to extract water in the future. Moreover, this strategy may become maladaptive in the long run, as found in the study by Jain et al. (2015) in Gujarat state where study area is located. Also, depletion of groundwater can increase energy consumption for pumping leading to a vicious cycle of increased energy demand, higher costs, and further depletion of groundwater resources. Further research is required to understand the hydrogeology of deeper aquifers in the region.

Finally, the common pool nature of groundwater may hinder adoption at the individual level of demand management interventions (Gardner et al., 1990; Asprilla-Echeverria, 2021). Given that farmers tap into a shared resource, cooperation at the village level and incentivization may be required to realize the benefits of drip adoption at the individual level. This is necessary to avoid the free rider problem. Also, while including psychological factors in the analysis enhances understanding, RANAS theory may not account for all psychological factors that hinder adoption, such as perceived fairness and technology acceptance (Contzen et al., 2023). Future studies could consider adding more factors to RANAS theory or testing alternative psychological theories to gain a deeper understanding of adoption barriers.

5 Conclusion

Increasing the adoption of agricultural water interventions by farmers is critical to adapting to water scarcity and ensuring the food and economic security of millions of farmers. However, despite the availability of a range of interventions and successful pilots, adoption remains low. This study assessed socioeconomic, biophysical and psychological factors influencing the adoption of two contrasting adaptation strategies, drip irrigation (demand management) and borewells (supply augmentation), in a semi-arid catchment in India. While drip irrigation is being promoted with government subsidies, borewells are being taken up by farmers using their own resources. The results show that psychological factors play a significant role in the adoption of both technologies, and incorporating these factors improved model explanatory power by almost threefold. The findings show that despite subsidies, drip irrigation adoption lags behind borewells, suggesting farmers' preference for supply augmentation measures. Farmers' perceived ability and positive beliefs about the benefits of drip systems are significant factors in adoption. Based on the results, the study suggests that a multi-pronged approach is necessary to increase the adoption of drip irrigation, including augmenting subsidies with efforts on extension services, post-adoption services, training, and awareness campaigns to build farmers' capacity and raise awareness. On the other hand, the increasing adoption of borewells is concerning, with implications for increasing socioeconomic inequality, indebtedness, and threatening deeper aquifers. Overall, it is critical to devise strategies that look beyond the socioeconomic factors to increase fair access to water resources while safeguarding against the overexploitation of groundwater.

Data availability statement

The datasets generated during and/or analyzed during the current study are available from https://doi.org/10.4121/e5dc84d4-e22e-41c3-aa41-fbbe7ec74d83.

Ethics statement

The studies involving humans were approved by Human Research Ethics Committee TU Delft (http://hrec.tudelft.nl/). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

MA: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. MM: Supervision, Writing – original draft, Writing – review & editing. AS: Supervision, Writing – original draft, Writing – review & editing. SP: Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing.

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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.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frwa.2024.1444423/full#supplementary-material

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