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Solar Irrigation for Agricultural Resilience

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Does solar irrigation threaten groundwater sustainability?

Evidence from India and Bangladesh

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Groundwater irrigation underpins South Asian agriculture but is increasingly unsustainable. Solar irrigation pumps (SIPs) are promoted to cut carbon emissions and subsidy costs, yet concerns persist about over-extraction. This study, under the SDC-supported SoLAR project, assesses two models: fee-for-service SIPs in Bangladesh and grid-connected SIPs in India. Results show no significant rise in groundwater use with solar adoption in these two models. In Bangladesh, operator-managed SIPs kept use in check despite cheaper costs, though some shift toward Boro paddy was noted. In India, grid-connected SIPs with feed-in incentives reduced water use in alluvial aquifers, while hard-rock systems showed little change. The findings highlight that groundwater impacts are context-specific, with well-designed solar models offering low-carbon irrigation without major sustainability risks.

Introduction

South Asia is the world's largest user of groundwater for agriculture, withdrawing large amounts (approximately 350 km^3 of groundwater) annually for irrigation[1]. It is estimated that there are roughly 30 million water extraction pumps in Bangladesh, India, Nepal and Pakistan. Groundwater pumping, fueled by either electricity or diesel has changed the landscape of agriculture in South Asia, and in recent decades has become a primary coping/adaptation strategy for farmers faced with climate variability and change. However, it comes with a substantial carbon footprint - 8-11% of the region's total carbon emissions[2,3]. Governments in South Asia are now increasingly promoting solar-powered irrigation pumps (SIPs) as a solution to mitigate this large carbon footprint while ensuring the livelihood of farmers are not compromised. There is sufficient evidence that solar irrigation also brings several socio-economic co-benefits through boosting farmers' food security, farm profitability, and reducing agricultural subsidy burdens[2].

While solar offers governments a low carbon alternative to diesel/electric pumps, concerns are being raised regarding the possible increase in groundwater abstraction with the widespread adoption of solar irrigation[4,5]. This concern stems from the zero marginal costs associated with solar irrigation, particularly in regions where previous efforts to reduce irrigation costs (such as highly subsidized electricity for groundwater pumping) have led to unsustainable rates of abstraction. This can manifest through over-irrigation, expansion of irrigated areas (for personal use or sale), or an increase in the cultivation of water-intensive crops. However, changes in farmers' irrigation behavior depend on a range of factors, including the type of solar irrigation model used (on or off-grid solar irrigation pumps), existing cropping patterns, surrounding value chain markets, and biophysical factors such as water availability (which depends on climate, aquifer type, and groundwater tables). Therefore, understanding how farmers' pumping behavior changes with the introduction of solar irrigation is critical to determining the expected impact on groundwater sustainability.

To address this issue, this first-of-its-kind study, part of the SDC supported Solar Irrigation for Agricultural Resilience (SoLAR) project in South Asia provides evidence and insight into farmers' water use and the impacts on groundwater resources through a multi-method approach in India and Bangladesh.

Solar irrigation and groundwater in Bangladesh

Bangladesh's Nationally Determined Contributions (NDC) roadmap highlights solar pumps as a key strategy to reduce agricultural GHG emissions by replacing diesel-based pumps. The government is actively scaling up solar irrigation to phase out diesel pumps. Infrastructure Development Company Limited (IDCOL), the leading financier of solar irrigation pumps, aims to install 50,000 SIPs by 2027[3].

In the region, the predominant solar irrigation model is the fee-for-service model. This model involves centralized sponsored solar irrigation pumps (SIPs) with power ranging from 5 kW to 20 kW (as shown in Figure 1a). These SIPs are centrally managed by a company that sells water to farmers in the designated command area through buried pipelines, replacing existing diesel pumps. In the future, there are plans to connect these few SIPs to the grid, and the operating company will have the option to evacuate excess energy based on feed-in-tariff. The implementation of centralised SIPs is growing at an accelerated pace in northwest Bangladesh (Figure 2(a)), a region which is characterized by high cropping intensity (>200%) mostly supported by groundwater irrigation (>95%), but also where groundwater sustainability is a major concern.

Research has shown that buying water from SIPs is significantly cheaper by 20%–30% compared to diesel irrigation and comes with ease of access in terms of operations[3]. However, there is concern that the relatively lower cost and ease of using SIPs (compared to diesel pumps) may increase groundwater abstraction. Currently, around 1.6 million pumps are used for groundwater irrigation in Bangladesh, with 80% being diesel pumps that irrigate approximately 80% of the total irrigated area[6].

In the north-central and north-west regions, this contribution is even higher, at 94%. Most of this irrigation is used for water-intensive dry-season rice (Boro paddy) cultivation, and the sustainability of groundwater irrigation in these regions is already under threat. The groundwater tables are still shallow in most wells but are declining, with about 65.7% of monitoring wells in the north-western region showing a significant falling trend over the period 1985–2016[6].

Additionally, increasing groundwater tables are breaching the suction limit of approximately 6 meters, rendering shallow tube wells (which account for about 86% of total wells) technically inoperable for the whole year.

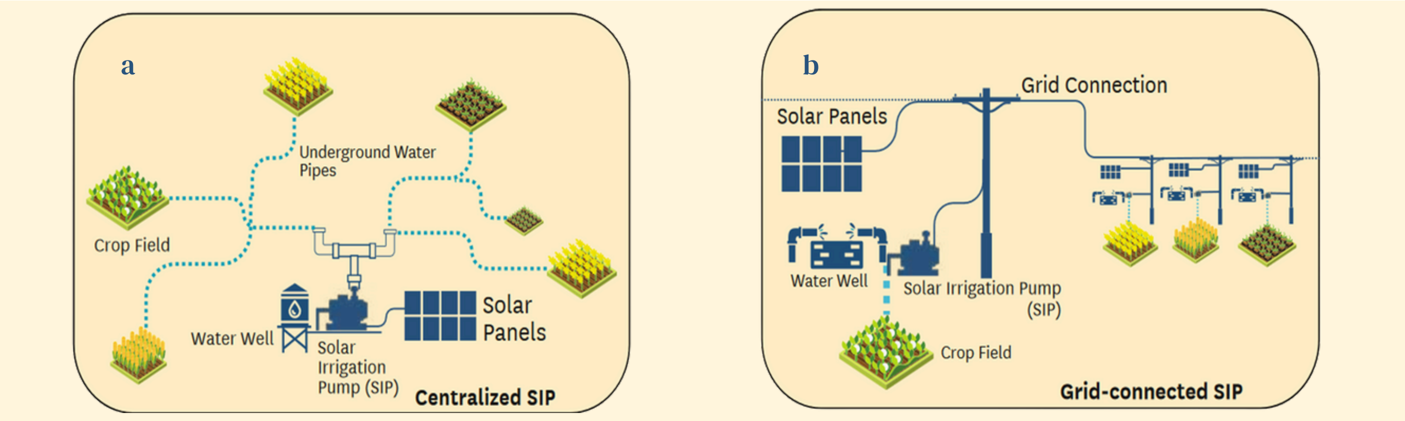

Figure 1. Schematic of (a) centralised SIP and (b) grid-connected SIPs

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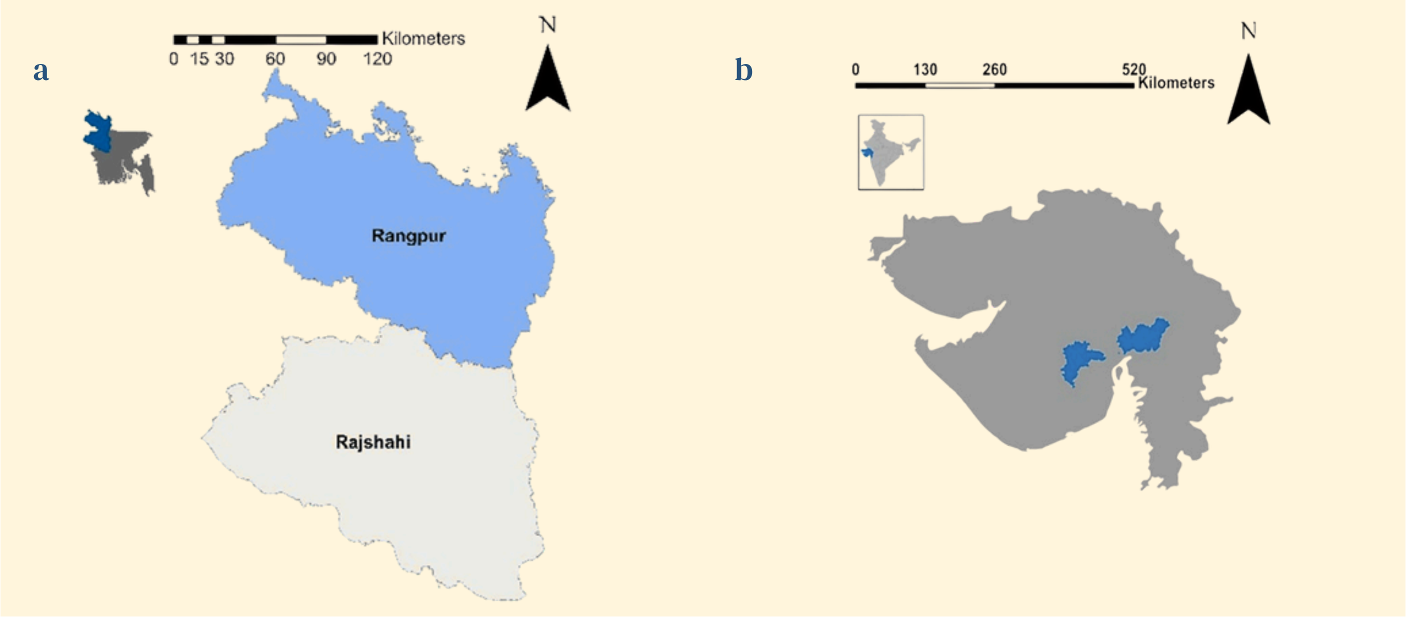

Figure 2. Study location in (a) Bangladesh and (b) India.

Solar irrigation and groundwater in India

Over the last decade, the Indian government is actively promoting solar irrigation through policies and programs to curb emissions from agriculture, but also to support farmer resilience considering growing climate variability and climate change. The flagship PM-KUSUM scheme, launched in 2019, seeks to solarize 3.5 million irrigation pumps in total, 2 million through standalone solar pumps, and 1.5 million by grid-connecting existing agriculture pumps[7]. In the latter case, a solar photovoltaic (PV) module of appropriate size is installed in the farmer's field, and the existing pump/ connection is metered in net terms, measuring the difference between energy exported to and drawn from the grid for pumping. As a result, the solar PV system generates and evacuates solar energy throughout the day, but the pump consumes electricity only when it is operating. Any excess energy generated is sold back to the grid, thus providing farmer the incentive to use energy (and water) more carefully and efficiently to maximise their income from selling energy.

It is critical to assess whether this grid-connected model of solar irrigation will ease or exacerbate existing groundwater sustainability. Approximately 14 million electric pumps, mostly running on subsidised electricity, have played a vital role in the expansion of groundwater irrigation to support rural livelihoods in India, but they have over time, also led to uncontrolled groundwater overexploitation in many parts of the country. Groundwater in Northwest and Southern Peninsular India, where most of these electric pumps are located, has seen widespread depletion. The Central Groundwater Board's (CGWB)[8] assessment reveals that 25% of assessed blocks, primarily in Northwest and Southern Peninsular India, are either overexploited or critical or semi-critical. Accessing deeper groundwater table also exacerbates quality issues by exposure to poorer-quality water due to increased susceptibility to saltwater intrusion, leading to potential land degradation. Further, continued unsustainable use of groundwater can reduce India's cultivated area by up to 20% and up to 68% in groundwater-depleted regions[9]. Given this context, this study examines the impact of grid-connected solar pumps on farmers' pumping behavior and its subsequent effect on overall groundwater resources.

The study is being conducted in Gujarat state (Figure 2(b)), where the grid-connected solar irrigation pump model has been implemented under the Suryashakti Kisan Yojana (SKY) scheme. More than 90 feeders have been solarized, with over 75% of farmers' irrigation pumps now being grid-connected solar.

Measuring and comparing farmers groundwater abstraction

The study collected data on the impact of solar irrigation on farmers water abstraction behaviour, taking a slightly different approach in India and Bangladesh to account for different solar irrigation models. The common denominator is the comparison of the groundwater abstraction behavior of solar farmers with that of non-solar farmers.
In Bangladesh, the water application of diesel and solar farmers for dry season rice, the main post-monsoon irrigated crop, was monitored at the farmer plot level on approximately 200 plots over two agriculture seasons (2021-2022 and 2022-23). The water application was monitored by combining instrumentation (flow meters in SIPs) (Figure 3a) and regular flow tests combined with farmer irrigation logbooks. SIP operators and diesel farmers were trained before monitoring began. This was complemented with panel data from 900 farmers to assess cropping changes, and the application of a regional groundwater model to simulate the impact of future solar irrigation energy transitions on groundwater sustainability.

In India, the project is using an energy-based approach to monitor farmer groundwater use[10], utilizing state-of-the-art energy monitoring data from the SKY scheme. This approach relies on converting farmers' pump energy use data to groundwater abstraction data based on a set of defined relationship. The energy-water conversion factor (power consumed/volumetric discharge) is derived by testing a representative set of pumps installed with flow meter (Figure 3 (b)) at different times of the year. The monitoring of approximately 200 farmers was carried out, including detailed data collection on their pumps, crops, pump flow rates, and energy use. This data was used to derive irrigation water application of farmers in 4 agricultural feeders, 2 each solar and non-solar in two districts of the state of Gujarat (Figure 2(b)).

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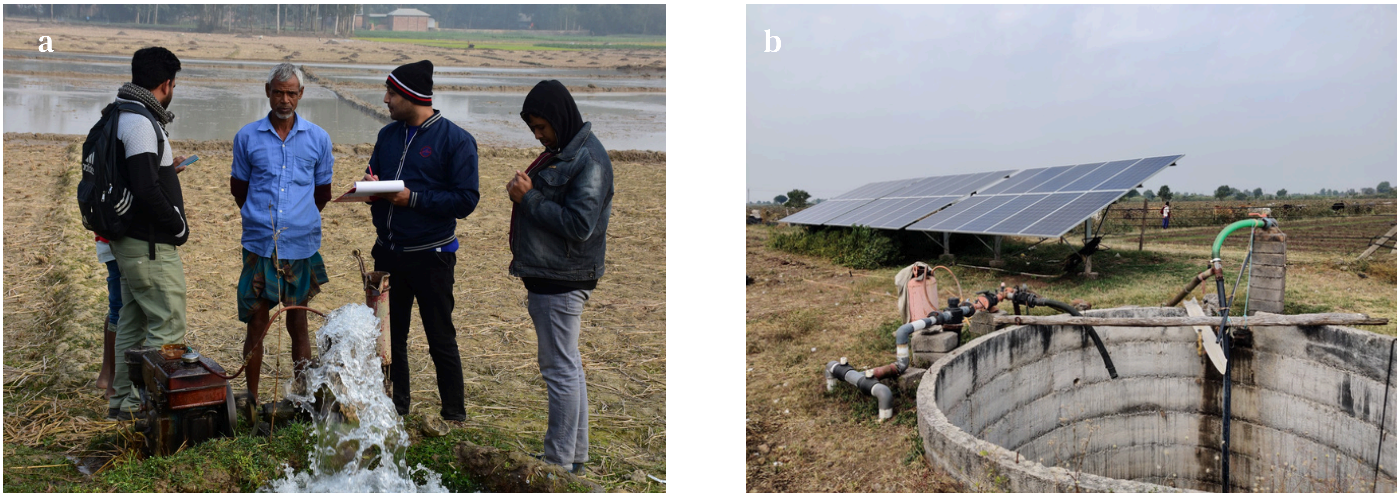

Figure 3. Measuring water application in (a) diesel and solar farmer plots in Bangladesh and (b) flow meter installed at farmers well in India. *(Photo: IWMI India)*

Results

Bangladesh

In Bangladesh, monitoring results from two years of dry-season paddy plots show that average irrigation water application depths for solar farmers ranged from 694 mm (2021–22) to 1014 mm (2022–23), compared to diesel farmers applying 663 mm (2021–22) to 775 mm (2022–23) (Figure 4). The lower irrigation for both solar and diesel farmers in 2021–22 was due to high rainfall (~500 mm in April–May). The findings showed that on average higher irrigation water application by solar farmers was influenced by non-energy factors such as crop variety, soil type, land elevation, and sowing time. However, after controlling for these plot-level characteristics using a random effects regression model, no statistically significant difference in water application between solar and diesel farmers was found. This is despite solar irrigation being 20–30% cheaper and more convenient under the fee-for-service model. This may be explained by the operational modalities (institutional set up and financing) of the fee-for-service irrigation model, where the irrigation service provider (sponsor) has a clear incentive to avoid over-irrigation to maximize the number of farmers that can be served by the pump, thereby optimizing revenue from water sales.

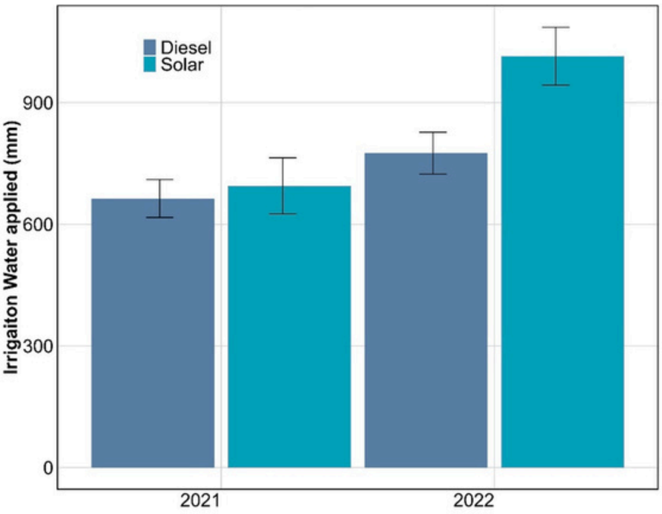

Figure 4. Irrigation Water application (mm) for Diesel and Solar farmers in Bangladesh.

Further, the farmer survey reveals no significant impact of solar pump access on the net cropped area or gross irrigated area of farmers, as northwest Bangladesh is already intensively cultivated and irrigated, leaving minimal fallow land to expand crop or irrigated land. However, solar farmers have a significantly higher dry-season paddy area by 4.2 percentage points (pp), primarily by shifting from other crops rather than expanding the total irrigated area. Given that 65–70% of the region is already under dry-season paddy, the possibility of expanding the area or irrigation is limited. However, this shift toward more water-intensive dry-season paddy could result in an overall increase in groundwater use due to its higher water demand compared to other crops. Regional groundwater modelling indicates minimal changes in groundwater levels (<1 m) under best-estimate scenarios of irrigation water application and dry-season paddy expansion, in the studied region suggesting a continuation of the status quo. However, significant increases in irrigation water application and dry-season area could raise sustainability concerns, in other regions, particularly in southern districts with thick Barind clay deposits and lower recharge rates, where groundwater declines of up to 3.3 m are projected under high abstraction scenario.

India

In India, results show that irrigation water application exhibits significant spatial and temporal variation influenced by cropping patterns, aquifer characteristics, and the type of irrigation feeder. Farmers in the Anand district applied substantially higher irrigation water (1,777–1,961 mm) compared to those in Botad (459–553 mm). This disparity reflects differences in cropping intensity and groundwater availability. Anand district has high cropping intensity (246–247%) which is driven by water-intensive crops (Paddy, Wheat and Tobacco) and supported by underlying productive alluvial aquifer. In contrast, Botad's lower cropping intensity (107–155%) is limited by its hard-rock aquifer system, which provides limited groundwater storage. Cropping patterns are dominated by kharif cotton and groundnut, with chana (gram) covering most of the rabi area.

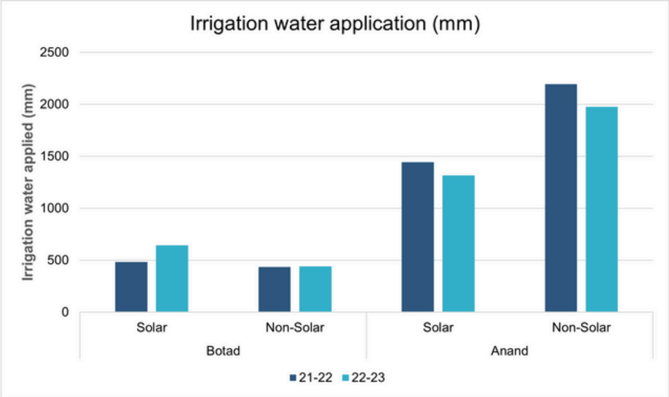

Figure 5. Irrigation Water application (mm) of solar and non-solar farmers in Anand and Botad district.

Comparing solar and non-solar feeders, water application was consistently lower in Anand district solar feeders (1,444 mm and 1,317 mm in the 2021–22 and 2022–23 seasons, respectively) compared to non-solar feeders (2,196 mm and 1,979 mm in the corresponding seasons) (Figure 5). In Botad, irrigation water application was comparable between solar (484 mm) and non-solar (436 mm) feeders in 2021–22, but in 2022–23, solar feeders exhibited a more significant increase (644 mm) compared to non-solar feeders (440 mm). This was accompanied by a larger reduction in irrigated area for solar feeders (from 3.9 ha to 2.3 ha) than non-solar feeders (from 3.9 ha to 2.9 ha) in year 2022-23 compared to 2021-22 due to poor monsoon and resultant groundwater constraints.

However, there are differences in these solar feeder's crop area, type and water selling dynamics. Since a direct comparison of irrigation water between solar and non-solar farmers could lead to biased estimates due to underlying differences in farmer characteristics, propensity score matching (PSM) was employed to ensure a more valid comparison of water use between the two groups. Controlling these factors revealed that solar irrigation adoption impacts water use differently across regions and years. In Anand, solar farmers significantly reduced irrigation water application (-608 mm in 2021-2022 and -363 mm in 2022-2023), while in Botad, differences were not statistically significant.

In alluvial aquifer regions like Anand, solar irrigation supported by financial incentives such as Feed-in-Tariffs and Evacuation-Based Incentives significantly reduced water use. In contrast, Botad's hard rock aquifers naturally constrain water availability and cropping intensity, limiting solar irrigation's impact on water use. These results highlight the context-specific impacts of solar irrigation and the importance of tailored policies.

Take aways

Scaling solar irrigation solutions presents a strategic pathway to improve the Water–Energy–Food nexus. This include providing opportunities to reduce the carbon footprint of groundwater irrigation while delivering both individual and societal co-benefits. This study examines two dominant solar irrigation models in South Asia—grid-connected solar irrigation in India and centralized solar irrigation pump schemes in Bangladesh—to generate empirical evidence on how access to solar irrigation influences irrigation practices as farmers transition from non-solar systems (diesel in Bangladesh and electricity in India) to solar.

Evidence from these models indicates that solar irrigation does not lead to a significant increase in water application when non-solar farmers transition to solar irrigation. In Bangladesh, this holds true despite solar irrigation being 20–30% cheaper and more convenient once provided as a service. In India, where grid-connected solar irrigation is supported by Feed-in-Tariffs and Evacuation-Based Incentives, results show evidence of reduction in water application in the Anand district, a district characterised by productive aquifer and water intensive irrigation. Importantly, the study highlights that non-energy factors—such as aquifer type, sowing dates, and crop variety—must be considered when assessing groundwater risks associated with solar irrigation. For the study regions, the results show that the examined solar irrigation models can be upscaled with minimal groundwater risks.

However, these findings are highly context-specific, reflecting agricultural–climatic conditions and the modalities of fee-for-service and grid-connected solar models. Outcomes may differ under alternative systems due to variations in hydrogeology, crop demand, price elasticity, aquifer characteristics, and the potential for expansion of irrigated or water-intensive crops. For instance, a slight increase in Boro paddy area (by 4.2 percentage points) as evident in Bangladesh underscores the need for carefully designed policies to scale up solar irrigation, particularly in groundwater-stressed regions. While the results are specific to the study areas and models, they carry important implications for India and Bangladesh, where such solar irrigation models are widespread and rapidly expanding.

To enhance generalizability, regional variation must be accounted for. For example, in areas with higher potential to expand net sown area, irrigation, or dry-season paddy cultivation, impact of lower irrigation costs (in Bangladesh for example) could be much higher incentivizing farmers to adopt more water-intensive practices—thereby amplifying the groundwater impacts of solar irrigation. Further, comprehensive understanding therefore requires comparing different solar implementation models—off-grid, grid-connected, and fee-for-service—since each generates distinct incentives that shape water use. For example, under fee-for-service schemes, water allocation is managed by an operator who earns revenue based on efficient delivery, incentivizing water use aligned with crop needs and enabling service to more farmers. Similarly, in grid connected solar incentives exist for evacuating energy. In contrast, under single ownership, where farmers own and operate solar pumps, the near-zero marginal cost of water may encourage over-irrigation. This is reflected in a previous study showing increase in groundwater use by solar farmers owners (individual)[11].

At the same time, there is need to integrate solar irrigation with water-saving irrigation technologies and improved agronomic practices, thereby improving low efficiency irrigation, mitigating groundwater risks and enhancing farmer benefits. This includes promoting micro-irrigation, diversifying cropping systems, and aligning solar irrigation with improved water and agronomy management. Overall,the results underline the need to avoid generalizing groundwater risks associated with solar irrigation and instead interpret them in relation to specific models and regional contexts. This underscores the importance of further research using causal methods to identify impacts across different solar irrigation models (such as off-grid and grid-connected systems) and the conditions under which they are applied.

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Project

The Solar Irrigation for Agricultural Resilience in South Asia (SoLAR-SA) project aims to sustainably manage the water-energy and climate interlinkages in South Asia through the promotion of SIPs. The main goal of the project is to contribute to climate-resilient, gender-equitable, and socially inclusive agrarian livelihoods in Bangladesh, India, Nepal and Pakistan by supporting government efforts to promote solar irrigation. This project responds to government commitments to transition to clean energy pathways in agriculture. All countries in this project have Nationally Determined Contribution (NDC) commitments to reduce greenhouse gas (GHG) emissions and SIPs can play a significant role in reducing emissions in agriculture. www.solar.iwmi.org

About SDC

The SoLAR -SA project is supported by the Swiss Agency for Development and Cooperation (SDC). SDC is the agency for international cooperation of the Federal Department of Foreign Affairs (FDFA). Swiss Agency for Development and Cooperation, which is an integral part of the Federal Council's foreign policy, aims to contribute to a world without poverty and in peace, for sustainable development. SDC, through its Global Programme Climate Change and Environment (GPCCE), helps find solutions to global challenges linked to climate change. It engages in global political dialogue and manages specific projects in the fields of energy, climate change adaptation, sustainable development of mountainous regions and prevention of natural hazards that are likely to influence regional and international policy.

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Disclaimer

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