RESEARCH ARTICLE
AGROBIOLOGICAL RECORDS
ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
Open Access Journal

SOLARIZATION AND GROUNDWATER DEPLETION: THE HIDDEN COSTS OF SOLAR-POWERED AGRICULTURE IN BALOCHISTAN, PAKISTAN

Ameenullah[1], Abdulaziz Thabet Dabiah [2], Raza Ullah[3], Syed Muhammad Khair[4], Syed Sadiq Agha[5], Rizwan Khan[6], Muhammad Muddassir [2]* and Mortala Boye[7]

[1]Department of Agricultural Economics, Balochistan Agriculture College, Quetta, Pakistan
[2]Department of Agricultural Extension and Rural Society, College of Food and Agriculture Science, King Saud University, Riyadh 11451, Saudi Arabia
[3]Institute of Agricultural and Resource Economics, University of Agriculture Faisalabad, Punjab, Pakistan
[4]Faculty of Agricultural Economics, University of Peshawar, Pakistan
[5]Value Chain Specialist, FAO
[6]Agriculture Production Specialist, FAO
[7]School of Agriculture and Environmental Sciences, University of The Gambia,
P. O Box 3530, Serekunda, The Gambia

**Corresponding author*: mrajpoot@ksu.edu.sa

ABSTRACT

Balochistan, Pakistan's arid south-western province, is experiencing a severe groundwater crisis, with levels falling by 5-40 feet per year due to an overreliance on tube wells for irrigation. This depletion endangers agricultural sustainability, particularly given the government's solarization policy, which aims to convert approximately 28,000 grid-connected tube wells to solar power. For the rural societies of Balochistan, groundwater is not merely an agricultural input but the singular economic lifeline upon which household income, food security, and intergenerational livelihoods are anchored, making any policy that alters extraction dynamics a matter of acute socioeconomic consequence. The socioeconomic fragility of these communities means they are simultaneously the primary drivers of groundwater stress and the most exposed to its depletion, a duality that demands urgent empirical attention. To date, no comprehensive research has been conducted to assess the impact of solar-powered electric tube wells (ETs) on groundwater resources in Balochistan. Combining farmers' perceptions with binary logistic regression analysis, this cross-sectional study was conducted during 2023 in three over-exploited highland basins of Balochistan – the Zhob River Basin (ZRB), the Nari River Basin (NRB) and the Pishin Lora Basin (PLB) – where water tables are falling by 10–40 feet per year. Using binary logistic regression on primary data collected from 320 proportionately stratified respondents, the study finds that solarization is the strongest single predictor of groundwater depletion ($\beta = 3.143$, odds ratio ≈ 23.2, $P<0.01$), while farmers' age ($\beta = 0.057$, $P<0.01$), irrigation frequency ($\beta = 1.768$, $P<0.01$) and water-table depth ($\beta = 0.004$, $P<0.01$) also significantly accelerate depletion; conversely, larger cultivated area is associated with more conservative water use ($\beta = -0.103$, $P<0.01$), whereas adoption of high-efficiency irrigation systems (HEIS) alone remains statistically insignificant ($\beta = -0.695$, $p = 0.159$). Unconditioned solarization will negatively impact the province's shallow aquifers, potentially leading to intergenerational disputes among key basin residents. To address this paradox, the study suggests combining solarization with mandatory HEIS adoption, implementing net-metering for solar wells, and improving water governance to protect shallow aquifers and ensure the long-term viability of agriculture in Balochistan.

Keywords: Solarization, Groundwater depletion, Electric Tubewells (ETs), High-efficiency irrigation systems (HEIS), Rural societies.

Article History: ABR-26-210 || Received: 05-Jun-2026 || Revised: 11-Jul-2026 || Accepted: 25-Jul-2026 || Published Online: 19-Aug-2026

1. INTRODUCTION

Pakistan's energy crisis is not merely an inconvenience; it severely constrains the country's economic and social development. Electricity shortages result in a loss of roughly 2% of the country's annual Gross Domestic Product (GDP), making them a major impediment to growth and economic progress (Irfan et al., 2019; Qamar et al., 2024). The crisis remains acute: urban centers continue to experience 10–12 hours of daily load-shedding, while many rural areas endure outages of 16–18 hours, underscoring the urgency of transitioning to renewable energy (Qamar et al.,

Citation: Ameenullah, Dabiah, A.T., Ullah, R., Khair, S.M., Agha, S.S., Khan, R., Muddassir, M. & Boye, M. (2026). Solarization and groundwater depletion: the hidden costs of solar-powered agriculture in Balochistan, Pakistan. Agrobiological Records, 25, 242-256. https://doi.org/10.47278/journal.abr/2026.060

ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
Open Access Journal

2024). These shortages affect sectors dependent on a stable energy supply, including households, businesses, industry, and agriculture. The agricultural sector is especially vulnerable because it depends on electricity for irrigation, a critical farming operation. The lack of reliable power sources in rural societies has reduced agricultural output, adversely affected livelihoods, and obstructed rural development (Yaqoob et al., 2021; Khan et al., 2025; Peer et al., 2026).

Despite its considerable renewable energy potential, particularly solar, Pakistan has so far been unable to integrate renewable energy at scale into its national grid. This underutilization has resulted in prolonged dependence on conventional energy sources, which are frequently expensive, unreliable and environmentally unsustainable (Wakeel et al., 2016). A transformation is nevertheless underway, particularly in rural communities, where solar systems are increasingly being deployed as an alternative energy source (Shah & Solangi, 2019; Peer et al., 2026). Solar energy is widely regarded as a viable solution to energy shortages, especially in agriculture, where an uninterrupted power supply is a prerequisite for irrigation. Balochistan, Pakistan's largest province by area, enjoys among the highest average daily sunshine hours in the world, making it an ideal location for solar energy development (Shah et al., 2018a; 2018b). Balochistan's abundant solar radiation offers a unique opportunity to power tube wells with solar PV systems, which are crucial for groundwater extraction and agricultural sustainability in the province (Ali et al., 2020; Peer et al., 2026).

1.1. Energy and Water Crisis in Balochistan

The transition to solar energy in Balochistan is taking place despite significant water shortages. Balochistan is currently experiencing severe water stress, exacerbated by recurrent droughts, insufficient rainfall, and over-dependence on groundwater. Groundwater is essential for water resource management, fulfilling irrigation water needs and supplying drinking water to a major portion of the population (Wakeel et al., 2016). Balochistan is experiencing a significant crisis, as groundwater tables in many regions are declining at alarming rates (Shah et al., 2018a; 2018b). Since the late 1990s, the groundwater table in most of Balochistan has been consistently declining, indicating extraction rates that significantly exceed natural replenishment. In Quetta, the provincial capital, groundwater levels have fallen to depths beyond 900-1300 feet in certain regions, presenting a significant risk to the city's three million residents (Khair et al., 2021; Mustafa et al., 2022). This depletion pattern is not limited to the capital city of Quetta but spreads throughout the province's highland regions. In the last four decades, regions such as Pishin, Kuchlak and Ziarat have experienced a decline in groundwater levels from 50-100 feet to 900-1500 feet, indicating significant overexploitation (Ashraf, 2020; Khan et al., 2025). In the Pishin Lora Basin (PLB), the Zhob River Basin (ZRB) and the Nari River Basin (NRB), groundwater levels are decreasing by 10 to 40 feet per year. Of the 18 basins in Balochistan, 10 are officially classified as over-exploited (Halcrow-Pakistan & Cameos, 2008; Rana et al., 2020; Khan et al., 2025). The rapid exhaustion of groundwater in these areas jeopardizes both agricultural viability and the availability of fresh water for local populations. If these patterns persist, Balochistan may face significant intergenerational challenges, including possible water conflicts among residents of different basins (Ahmad, 2006; Peer et al., 2026).

1.2. Political Economy of Groundwater Development

Groundwater development has long been employed as a prominent policy tool in numerous developing nations, including Pakistan, to enhance agricultural growth. Nonetheless, these regulations frequently result in unforeseen environmental and societal consequences. Groundwater is a common-pool resource, characterized by non-excludability and rivalry (subtractability) in consumption, which complicates effective regulation without robust institutional governance. In Balochistan, inadequate institutional frameworks have led to irrational extraction, resulting in the unsustainable depletion of groundwater resources (Nagaraj et al., 1999). Government initiatives aimed at promoting groundwater development, such as tube well electrification and subsidies, have exacerbated the issue, leading to over-extraction of this resource.

A key policy in Balochistan that contributes to groundwater over-extraction is the subsidization of electricity for agricultural tubewells. Intended to enhance agricultural output by reducing irrigation costs, these incentives have increased the use of electric tubewells. From the late 1980s to 2008, the number of tubewells in Balochistan surged significantly, specifically in the Pishin Lora Basin, Zhob River Basin, and Nari River Basin, which are home to 40-45% of the province's populace (Khair et al., 2021). Fig. 1 illustrates the rapid proliferation of tubewells, with the province's total exceeding 62000 registered wells by 2020, in addition to an anticipated 21300 unregistered wells (Rana et al., 2020; GOB, 2021-2022). Though these strategies have enhanced agricultural production, they have simultaneously resulted in significant environmental deterioration. Subsidized energy has enabled farmers to pump groundwater at unsustainable levels. In 2015, farmers incurred a fixed flat-rate electricity cost of 10,000 rupees, which accounted for merely 10% of the total expenditure, while the remaining operational costs were effectively absorbed through government-supported subsidies and reduced tariff structures. This artificial reduction in extraction costs has weakened conservation incentives and encouraged excessive pumping even in areas already experiencing critical

Citation: Ameenullah, Dabiah, A.T., Ullah, R., Khair, S.M., Agha, S.S., Khan, R., Muddassir, M. & Boye, M. (2026). Solarization and groundwater depletion: the hidden costs of solar-powered agriculture in Balochistan, Pakistan. Agrobiological Records, 25, 242-256. https://doi.org/10.47278/journal.abr/2026.060

ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
Open Access Journal

groundwater stress.

As a result, aquifer levels across major basins have declined steadily, increasing pumping depths and raising long-term extraction costs for farmers. This creates a feedback loop in which declining water tables necessitate deeper drilling and more powerful pumping systems, further increasing energy demand and reinforcing dependence on subsidized electricity. Over time, such dynamics disproportionately benefit larger landowners who can afford additional deep tubewell investments, while marginal farmers face reduced access to groundwater or are forced to abandon cultivation altogether. Consequently, socio-economic inequality in rural agricultural systems has widened.

Moreover, the environmental consequences extend beyond depletion. Falling groundwater levels have also contributed to deteriorating water quality, as increased salinity and mineral concentrations in deeper aquifer layers reduce crop yields and soil productivity. The lack of effective regulatory monitoring and enforcement mechanisms has further intensified the tragedy of the commons, in which individual users, acting in rational self-interest, collectively degrade a shared resource. In the absence of institutional reforms, demand-side management, and efficient pricing structures, the current subsidy regime continues to undermine long-term groundwater sustainability in Balochistan, despite its short-term gains in agricultural output.

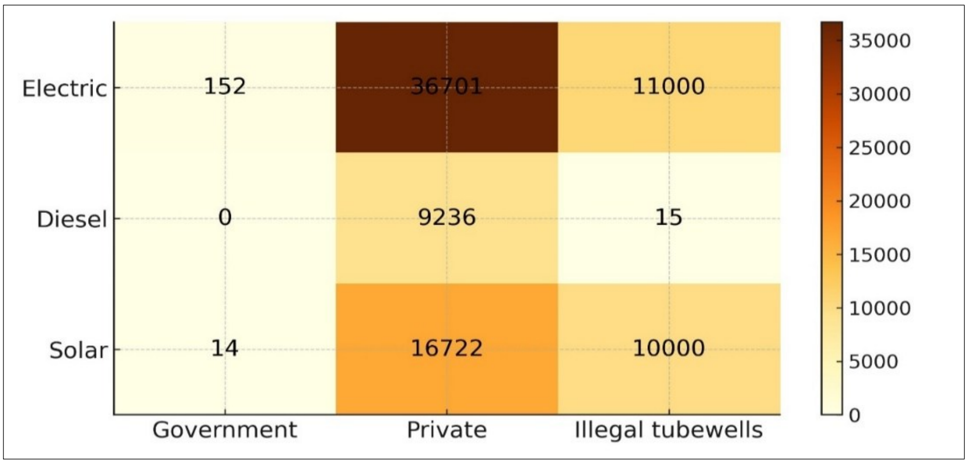

Fig. 1: Total Number of Tube Wells in Balochistan by Government and Private Sector. Source: (Rana et al., 2020; GoB, 2021-2022; Field survey, 2023). This has imposed a substantial financial strain on the government, leading to the rapid exhaustion of groundwater supplies (Ahmad, 2006; GOB, 2021-2022; Rafi-Khan & Maria, 2023).

1.3. The Solarization Initiative: A Double-Edged Sword

In light of the financial and environmental issues associated with tubewell irrigation, the Balochistan government has proposed an ambitious initiative to convert the province's 28,000 grid-connected tubewells to solar power. The solarization program, anticipated to cost Rs55 billion, shared between the federal and provincial governments on a 70:30 basis (DAWN, 2024), seeks to eliminate power subsidy burdens, boost energy security, and release scarce grid capacity for alternative uses, perhaps mitigating the province's current power deficit (DAWN, 2024). Solar-powered tubewells have the potential to transform the agricultural sector by providing a reliable, cost-effective energy source for irrigation, thereby reducing financial burdens on farmers and the government (Peer et al., 2026).

This policy shift, however, carries serious risks of its own. The implementation of autonomous, solar-powered tubewells that operate independently of the national energy grid may lead to unregulated groundwater extraction. Inadequate regulation significantly intensifies the risk of worsening groundwater depletion, especially in regions such as Balochistan, where groundwater recharge is inherently weak owing to scanty rainfall (250-300 mm annually) and limited surface water resources. Solar-powered irrigation systems, although environmentally beneficial in terms of energy use, may exacerbate the region's severe water shortage if not properly regulated (Khan et al., 2025).

In rural Balochistan, groundwater extraction through tube wells is not merely an irrigation practice; rather, it is the structural foundation of an agrarian economy that sustains millions of smallholder households across ecologically fragile highland basins. Farming families in areas such as the Zhob, Nari, and Pishin Lora basins depend on subsurface water for every stage of agricultural production, and by extension, for income generation, debt repayment, and basic food provisioning (Hanjra & Qureshi, 2010; Watto & Mugera, 2016). This socioeconomic dependence is so deeply embedded that fluctuations in groundwater availability translate directly into household poverty, seasonal migration, and long-term agrarian distress (Qureshi et al., 2022). It is within this context of structural water dependency that the government's solarization initiative must be critically examined, as policies designed to reduce energy costs for irrigation inevitably reshape the incentive structures governing how much water rural societies extract, when, and at what ecological cost (Shah, 2022; Ahmad et al., 2023)

1.4. Groundwater Development Policies and their Implications

The government's groundwater development initiative in Balochistan has focused primarily on expanding

Citation: Ameenullah, Dabiah, A.T., Ullah, R., Khair, S.M., Agha, S.S., Khan, R., Muddassir, M. & Boye, M. (2026). Solarization and groundwater depletion: the hidden costs of solar-powered agriculture in Balochistan, Pakistan. Agrobiological Records, 25, 242-256. https://doi.org/10.47278/journal.abr/2026.060

irrigated agriculture through the installation of tubewells. The spread of tubewells has enabled farmers to grow high-value crops, including fruits and vegetables, thereby encouraging the region's economic development. Nonetheless, these advancements have resulted in significant environmental impacts, particularly groundwater depletion. In 2008, there were approximately 2123 tubewells in Balochistan, representing 62% of the province's total wells, mainly located in the Pishin Lora, Zhob, and Nari River Basins (WAPDA, 1993). Fig. 2 illustrates a significant reduction in groundwater levels in these basins, with the water table decreasing from 50-100 feet to over 200-800 feet within a decade (Ahmad, 2006).

This rapid decline in groundwater levels has increased reliance on deeper, more energy-intensive pumping systems. As a result, irrigation production costs have risen, particularly for smallholder farmers who lack the capital for advanced technologies. The over-extraction trend has also reduced the natural recharge capacity of aquifers, making recovery increasingly difficult even during favorable rainfall periods. In many areas, traditional water sources such as karezes have dried up, further intensifying pressure on tubewells. Moreover, declining groundwater quality, including rising salinity levels, has begun to affect soil fertility and crop yields. The absence of effective monitoring and regulatory enforcement has further accelerated unsustainable abstraction practices. Consequently, groundwater depletion in these basins now poses a serious threat to long-term agricultural sustainability in the province.

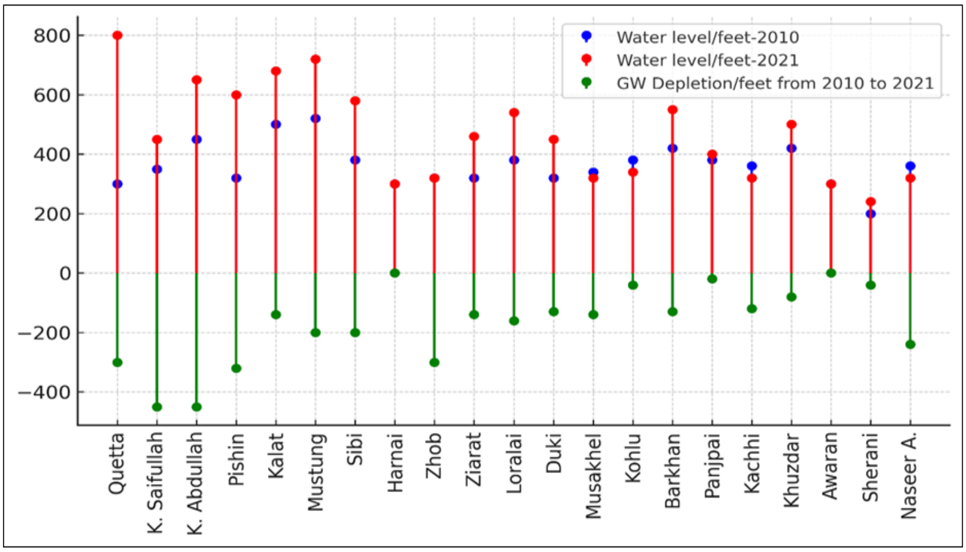

Fig. 2: Declining Groundwater Levels in Balochistan. Source: (Ahmad, 2006; GOB, 2021-2022).

The dependence on electric- and diesel-powered tubewells, combined with over-extraction, has adversely affected the traditional Kareze irrigation system, which has historically been important to Balochistan's community water management. The Kareze system, consisting of underground canals that convey water from aquifers to surface regions for irrigation, has been used for centuries but is currently in decline due to the widespread adoption of tubewells. Karezes, which previously accounted for 60% of irrigation systems in districts such as Killa Saifullah, Loralai, Pishin, and Ziarat, are rapidly disappearing (Ashraf, 2020).

1.5. Problem Statement

This study thoroughly analyses farmers' perspectives on the solarization program for tubewells in Highland Balochistan, emphasizing the associated social and environmental threats. The principal issue is the potential for unregulated water withdrawal from independent solar-powered tube wells, which may aggravate groundwater depletion in an area already experiencing significant water scarcity, as autonomous solar systems allow farmers to pump throughout the daylight hours at virtually no marginal cost (Fig. 3).

This study critically evaluates the perceptions of the agricultural community and examines the key deficiencies in the solarization policy. A primary concern is the diminished control over the functioning of these autonomous solar-powered tube wells, which may exacerbate the depletion of already strained groundwater resources. The study assesses whether the policy of solarising tube wells is detrimental or beneficial for agriculture in the highlands of Balochistan. This study investigates whether solarization can offer a sustainable solution to severe water scarcity or exacerbate the problem. The investigation examines the complex trade-offs, weighing the economic incentives for adopting solar technology against the potential impacts on groundwater sustainability.

ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
Open Access Journal

Fig. 3: Groundwater extraction with the use of solar power (original field photograph taken by the authors during the 2023 survey). Source: Field survey, 2023.

1.6. Global Evidence, Knowledge Gap, Objectives and Hypotheses

The concerns motivating this study resonate strongly with recent international evidence. Across low- and middle-income countries, solar-powered groundwater irrigation is expanding exponentially, and behavioural evidence indicates that the near-zero marginal cost of solar pumping systematically encourages additional extraction unless it is paired with credible regulation or counter-incentives (Balasubramanya et al., 2024). In South Asia, Shah et al. (2018a; 2018b) warned that the region's energy–rapidly multiplying, unregulated solar pumps could destabilize the groundwater nexus, while empirical evidence from Rajasthan, India, shows that solar-pump adopters increased both irrigated area and groundwater extraction relative to non-adopters (Gupta, 2019). Globally, Jasechko and Perrone (2021) demonstrate that shallow wells of the kind that dominate Balochistan's highland basins are the first to run dry when water tables decline, and Jain et al. (2021) project that unchecked depletion severely curtails future cropping intensity. Comparable governance dilemmas have been documented for Sub-Saharan Africa and the Middle East, where inclusive solar-irrigation frameworks are advocated precisely because technology deployment has outpaced water governance (Closas & Rap, 2017; Lefore et al., 2021). Pakistan itself exemplifies this trajectory of colossal groundwater development accompanied by neglected management (Qureshi, 2020).

Despite this growing international literature, a clear knowledge gap persists: no comprehensive empirical study has yet combined farmers' perceptions with econometric analysis to quantify the effect of tubewell solarization on groundwater depletion in the over-exploited highland basins of Balochistan – the very province where Pakistan's largest solarization programme is being implemented. The novelty of the present study therefore lies in (i) providing the first basin-level, farmer-centred evidence on the solarization–groundwater nexus in Balochistan and (ii) integrating perception analysis with binary logistic regression to identify the socioeconomic and technical drivers of depletion.

Accordingly, the specific objectives of the study are: (1) to document farmers' perceptions of the causes of groundwater depletion, groundwater ownership and related government policies in the Zhob, Nari and Pishin Lora basins; (2) to quantify the effect of tubewell solarization and key socioeconomic variables on groundwater depletion using binary logistic regression; and (3) to derive policy measures that reconcile solar energy adoption with sustainable aquifer management. The study tests three hypotheses: H1 – solarization of tubewells is positively and significantly associated with groundwater depletion; H2 – farmers' socioeconomic characteristics (age, education, cultivated area) and irrigation behaviour (irrigation frequency, water-table depth) significantly influence groundwater depletion; and H3 – adoption of high-efficiency irrigation systems (HEIS) is negatively associated with groundwater depletion.

2. MATERIALS AND METHODS

2.1. Study Area

This research was conducted in Balochistan, a Southwestern region of Pakistan, covering over 347,190 square kilometres and situated between latitudes 25°-32° N and longitudes 61°-71° E. Balochistan, characterized by an arid environment and average annual rainfall below 250 mm, predominantly depends on groundwater for agricultural purposes (GOB, 2021-22). The highlands region, one of the province's six agroecological zones, is arid, receiving only 200-250 mm of rainfall annually, underscoring the need for sustainable irrigation supplies (IUCN, 2000). This area comprises the Zhob River Basin (ZRB), the Nari River Basin (NRB), and the Pishin Lora Basin. In the study, the highlands were categorized by elevation into low-altitude areas (1050-1550 meters), medium-altitude areas (1551-2050 meters), and high-altitude areas (above 2051 meters), acknowledging the varied climatic, agricultural, and water resource conditions at these elevations (Choudhary et al., 2008; Rana et al., 2020). Climatically, the highlands experience cold, semi-arid winters and warm, dry summers, with pronounced inter-annual rainfall variability and recurrent droughts that severely constrain natural aquifer recharge (GOB, 2021-22). The geographical locations of the three studied basins are shown in Fig. 4.

2.2. Questionnaire Design and Sampling Framework

A comprehensive, structured questionnaire was created; its content validity was evaluated by a panel of research experts in agricultural economics and water resource management, and it was refined based on their feedback and a field pre-test conducted with farmers outside the final sample to remove ambiguous items and ensure data reliability. Ethical research protocols were observed throughout the survey: participation was entirely voluntary, informed consent was obtained from every respondent prior to the interview, and the anonymity and confidentiality of all

Citation: Ameenullah, Dabiah, A.T., Ullah, R., Khair, S.M., Agha, S.S., Khan, R., Muddassir, M. & Boye, M. (2026). Solarization and groundwater depletion: the hidden costs of solar-powered agriculture in Balochistan, Pakistan. Agrobiological Records, 25, 242-256. https://doi.org/10.47278/journal.abr/2026.060

ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
Open Access Journal

responses were guaranteed, with the data used exclusively for research purposes. The Department of Agriculture provided a comprehensive list of villages in the three basins, which served as a representative sampling frame. Sample villages were selected to reflect the diverse topographic conditions of the study area accurately.

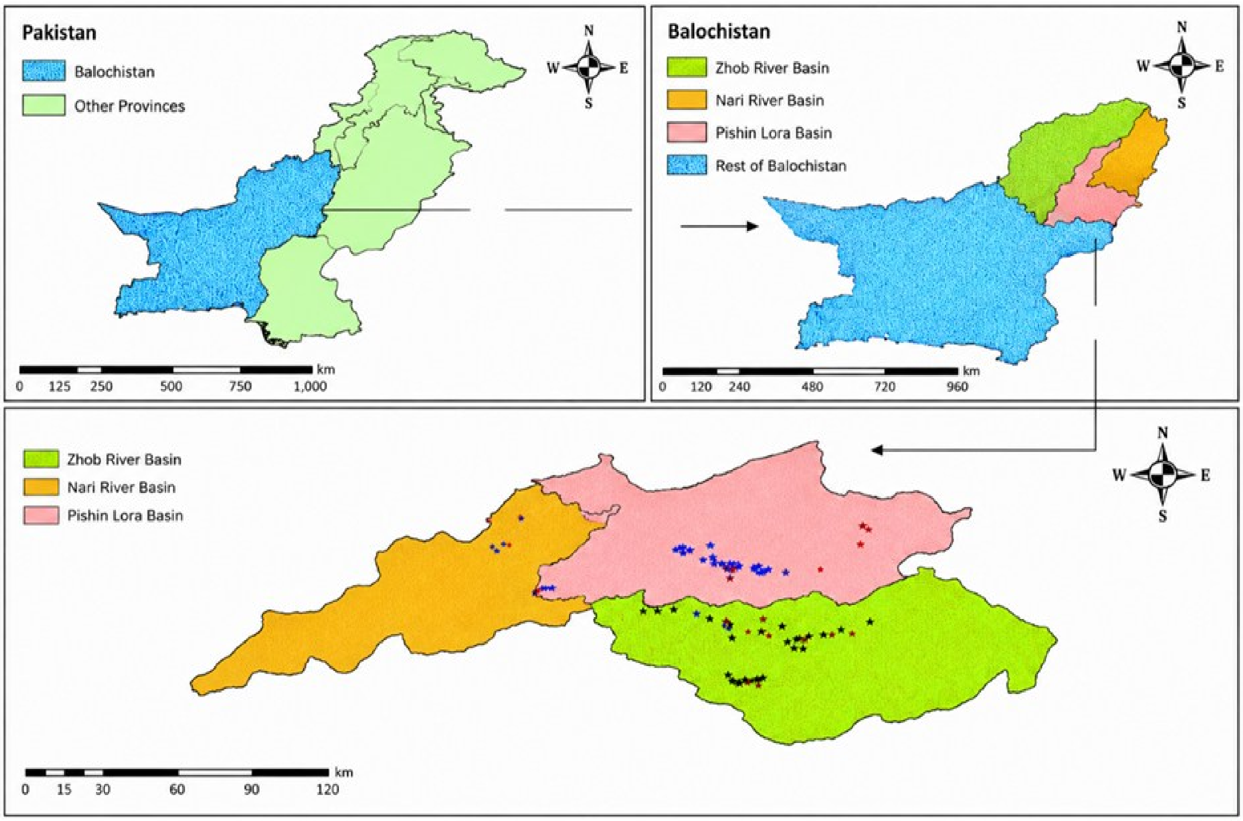

Fig. 4: Map of the study area showing the Zhob River Basin, Nari River Basin and Pishin Lora Basin, Highland Balochistan, Pakistan.

2.3. Sample Size Selection and Data Collection

The highlands were selected from among the six agroecological zones owing to their declining groundwater levels and acute water constraints. In this area, three principal basins were purposively selected: the Zhob River Basin (ZRB), the Nari River Basin (NRB), and the Pishin Lora Basin (PLB). Primary data were gathered from five purposively selected settlements within each basin. Using the formula by Yamane (1967), $n = N/(1 + N*e^2)$, a representative sample of 350 respondents was selected through a proportionate stratified sampling technique. The questionnaire was administered through face-to-face interviews by trained and closely supervised enumerators. During data screening, 30 questionnaires were excluded because of incomplete or internally inconsistent responses on key variables, yielding 320 valid observations (an effective response rate of 91.4%) that were used in the descriptive analyses; one further observation with a missing value on an explanatory variable was dropped through listwise deletion at the estimation stage, so the logistic regression was fitted on 319 complete cases.

2.4. Econometric Modelling

2.4.1. Logit Regression: The binary logistic regression technique is commonly employed in empirical research to analyze and forecast dichotomous outcomes, such as the adoption or non-adoption of a technology (Sanni & Doppler, 2007; Banerjee & Martin, 2009). The cumulative logistic probability model (Aidoo et al., 2013) is presented thus;

$$P_i\left(Y = \frac{1}{X_i}\right) = f(Z_i) = \frac{1}{1 + e^{-(\alpha + \beta_i X_i + \varepsilon_i)}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (01)$$

Where P_i = probability that a farmer is an adopter of HEIS in the face of explanatory variables (X_i) and P_i ranges between 0 to 1, e = natural logarithm base, X_i = the vector of an independent variable, α and β_i = the model parameters to be estimated, and ε_i = the stochastic error term.

ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
Open Access Journal

The model is expressed in terms of odds and log-odds to make the estimated coefficients easier to interpret. Therefore, the odds ratio is the ratio between the probability that a farmer will adopt HEIS (P_i) to the probability that a farmer will not adopt HEIS $(1 - P_i)$.
Thus;

$$e^{z_i} = \frac{P_i}{1 - P_i} \quad \ldots \ldots (02)$$

$$\ln\left(\frac{P_i}{1 - p_i}\right) = z_i \quad \ldots \ldots (03)$$

$$Z_i = \alpha + \sum_{1=0}^{n} \beta_i X_i + \varepsilon_i \quad \ldots \ldots (04)$$

By the introduction of a dichotomous response variable, Y_i, $Y_i = \begin{cases} 1 \text{ if } Y^* > 0 \\ 0 \text{ otherwise} \end{cases}$

where 1 = adopters, 0 = non-adopters, i = total number of respondents, Solving for the probability that Y = 1, Equation becomes,

$$\left(\frac{P_i}{1-P_i}\right) = e^{z_i} \quad \ldots \ldots (05)$$

Then,

$$P_i = \frac{e^{z_i}}{1+e^{z}} \quad \ldots \ldots (06)$$

2.4.2. Validity and Reliability: This study addressed validity and reliability to ensure dependable outcomes. Validity was strengthened through expert review of the questionnaire, pre-testing, and achieving an adequate sample size, in line with Hair et al. (1998) guidelines. Triangulation, or mixed methods, was also applied to enhance qualitative validity (Maxwell, 2013). Reliability, defined as consistency in research methodology (Saunders et al., 2015; Khan et al., 2025), was maintained by including diverse farmer groups in sampling, training and monitoring enumerators, and pre-testing the survey instrument to eliminate ambiguous questions. A Cronbach's Alpha of 0.67 was calculated, indicating acceptable reliability for sociological research (Louangrath, 2018; Wudil et al., 2023).

Explanatory variables for the logistic model were selected based on economic theory, prior empirical studies on groundwater depletion and solar irrigation (Qureshi et al., 2008; Gupta, 2019; Khan et al., 2025), and preliminary diagnostic checks for multicollinearity among candidate regressors before inclusion in the final specification. All statistical analyses were performed using Stata version 17.0 (StataCorp LLC, College Station, TX, USA).

3. RESULTS

Table 1 shows that groundwater depletion emerges from its open-access nature and lack of regulation. Key factors include low rainfall (<250 mm/year), high water-demand crops (750 mm/year), widespread unregulated tubewell drilling, inefficient irrigation, and prolonged over-pumping due to energy subsidies (Ahmad, 2006). The survey data highlight respondents' perceptions of the causes of groundwater depletion in highland Balochistan, illustrating distinct priorities across electric, solar, and combined electric-solar tubewell users. Among electric tubewell users, nearly half (48.37%) identified low aquifer recharge as the primary cause for groundwater decline, suggesting a sound awareness of environmental constraints. This is further supported by the finding that 37.21% attribute the depletion to the mass installation of tubewells, indicating that overuse of groundwater infrastructure is perceived as a significant contributing factor. Additionally, cropping intensity was noted by 6.98% of electric tubewell users, consistent with prior research (Khair et al., 2012; Khan et al., 2025), which observed that cultivating high-water-demand crops, like apples, is associated with lowered water tables. These findings highlight the ecological strain imposed by intensive agriculture in areas reliant on groundwater.

Users of solar tubewells, however, prioritized different factors: depletion was mostly attributed to subsidized electricity (28%), followed by inadequate aquifer replenishment (22%) and extensive tubewell installations (20%). This perspective indicates that economic incentives might unintentionally encourage over-extraction of groundwater, a notion supported by Ahmad (2006) and Qureshi et al. (2008), who found that higher energy costs and inadequate water management practices intensify groundwater depletion in the area. Users of combined electric-solar systems predominantly identified low aquifer recharge (30%) and extensive tubewell installations (22%) as contributing factors, while acknowledging cropping intensity at 14%, indicating a balanced concern regarding both infrastructure and agricultural intensity.

Collectively, the responses suggest that participants recognize natural constraints, such as insufficient aquifer recharge, and human-induced pressures, including widespread tubewell installations and high-water-demand crops, as significant factors contributing to groundwater depletion. The evidence corroborates the concerns raised by Qureshi et al. (2008), who noted that declining water tables result in escalating pumping costs and declining groundwater quality, and by Rizwan et al. (2021), who forecasted that ongoing groundwater extraction may lead to intergenerational sustainability challenges and water conflicts. Given that more than 60% of Balochistan's groundwater has been depleted (Ahmad, 2006; Rana et al., 2020; Khan et al., 2025), these findings underscore the critical necessity for strategic groundwater management and a reassessment of agricultural and economic strategies to guarantee water security for present and future generations.

Table 1: Perception of the respondents about the causes of groundwater depletion

Reasons for water table decline	Electric tubewell users		Solar tubewell users		Electric + Solar tubewell users	
	Freq.	Percent	Freq.	Percent	Freq.	Percent
Cropping intensity	15	6.98	4	8.00	7	14.00
Subsidized electricity	3	1.40	14	28.00	1	2.00
Low aquifer recharge	104	48.37	11	22.00	15	30.00
Inefficient irrigation techniques	3	1.40	2	4.00	8	16.00
Mass installation of tubewells	80	37.21	10	20.00	11	22.00
Solarization	15	4.65	8	18.00	8	16.00
Total	220	100	50	100	50	100

Source: Field survey, 2023.

3.1. Groundwater Ownership and Government Policies

Table 2 provides critical insights into users' perceptions of electric, solar, and combined electric-solar tubewells concerning government groundwater policy, their readiness to adopt solar energy, and their opinions on groundwater ownership. A striking observation is the pervasive lack of awareness of groundwater-related policies across all respondent groups. Among electric tubewell users, 81.82% reported being uninformed of any policies, whereas only 0.45% confirmed the presence of a policy, and 17.73% stated categorically that no policy was in effect. A comparable trend is observed among solar tubewell users: 65% report no knowledge of any groundwater-related government regulation, and 32.50% assert that no such policy exists. The collective cohort of electric and solar tubewell users exhibited significant unawareness, with 87.50% of respondents reporting unfamiliarity with the policies. These findings indicate a significant deficiency in the communication or implementation of governmental groundwater management policies, especially in a region where water shortage is becoming an increasingly urgent concern. If policies are in place, they have not been sufficiently communicated to the agricultural communities and essential players involved in groundwater resource management. These findings are consistent with the empirical evidence reported by Khan et al. (2025) and Peer et al. (2026).

The second section of the table analyses respondents' readiness to shift to solar energy upon receiving subsidies for solarization. Among solar tubewell users, 65% indicated a preference to discontinue electricity usage, demonstrating this group's positive attitude towards solar energy. Conversely, only 36.36% of electric tubewell users expressed a willingness to discontinue electricity use if offered solarization incentives, while 59.55% indicated they would continue using electricity. This indicates substantial reluctance or dependence on existing electricity systems among this group, likely attributable to established infrastructure or a perceived lack of reliability in solar systems. Sixty percent of combined users indicated a readiness to fully migrate to solar energy, reflecting a favorable attitude towards adopting solar-powered irrigation systems. The significant percentage of electric tubewell users resistant to transition underscores potential obstacles to adopting renewable energy, especially if electricity remains subsidized or more readily available.

The final section of the table examines perceptions of groundwater ownership, which varied markedly across populations. Among electric tubewell users, 43.64% perceived groundwater as private property, reflecting a robust belief in individual ownership of this common-pool resource. A substantial percentage (23.18%) perceived groundwater as belonging to God, indicating a communal or spiritual viewpoint on natural resources, whereas 26.36% regarded it as public property. Conversely, among solar tubewell users, a clear majority (55%) regarded groundwater as divinely owned, indicating a more communal and spiritual perspective on water resources within this demographic. Merely 25% regarded it as private property, while 15% perceived it as public property. Notably, of all users, 52.50% perceived groundwater as public property, 32.50% attributed ownership to God, and barely 5% regarded it as private property. The varied perspectives on groundwater ownership underscore the socio-cultural intricacies of groundwater regulation and management. The prevalence of community or spiritual perspectives on water resources, especially among solar and mixed users, may challenge laws aimed at regulating or privatizing groundwater extraction. Effective water management methods must account for these differing ideas of ownership to ensure that restrictions are socially accepted and enforceable.

ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
Open Access Journal

Table 2: Respondents' perceptions of groundwater ownership and the Govt policies

GW ownership and policies	Electric tubewell users		Solar tubewell users		Electric + Solar tubewell users	
	Freq.	Percent	Freq.	Percent	Freq.	Percent
Is there any government groundwater-related policy in effect?						
Yes	1	0.45	1	2.50	2	5
No	39	17.73	13	32.50	3	7.50
Don't know	180	81.82	26	65	35	87.50
Total	220	100	40	100	40	100
Is solarization of electric tubewells an economically and environmentally viable policy						
Yes	80	36.36	26	65	24	60
No	131	59.55	9	22.50	12	30
Don't know	9	4.09	5	12.50	4	10
Total	220	100	40	100	40	100
Groundwater ownership						
God	51	23.18	22	55	13	32.50
State	15	6.82	2	5	4	10
Public property	58	26.36	6	15	21	52.50
Private property	96	43.64	10	25.00	2	5.00
Total	220	100	50	100	50	100

Source: Field survey, 2023.

3.2. Perception of the Respondents about Existing and Future Govt. Legislations

Fig. 5 indicates that although the solarization of tubewells is perceived as a feasible and dependable approach by 65% of Solar Tubewell users and 50% of Electric and Solar Tubewell users, it directly exacerbates groundwater depletion. Solar tubewells, regarded as more dependable by 75% of their users and 60% of users of both electric and solar tubewells, can function with fewer financial limitations than electric tubewells. This results in over-extraction, especially in regions experiencing declining groundwater levels. Moreover, 87.5% of users of Electric and Solar Tubewells are unaware of any governmental policy regarding groundwater, underscoring a lack of awareness or enforcement of restrictions. Moreover, 55% of Solar Tubewell users saw groundwater as "owned by God," thereby diminishing their sense of human accountability for sustainable water utilization. Consequently, although solarization is regarded favorably, it exacerbates groundwater depletion in the research area, necessitating the immediate establishment of more robust regulatory frameworks and heightened awareness to foster sustainable groundwater management. These findings are consistent with the empirical evidence reported by Khan et al. (2025) and Peer et al. (2026).

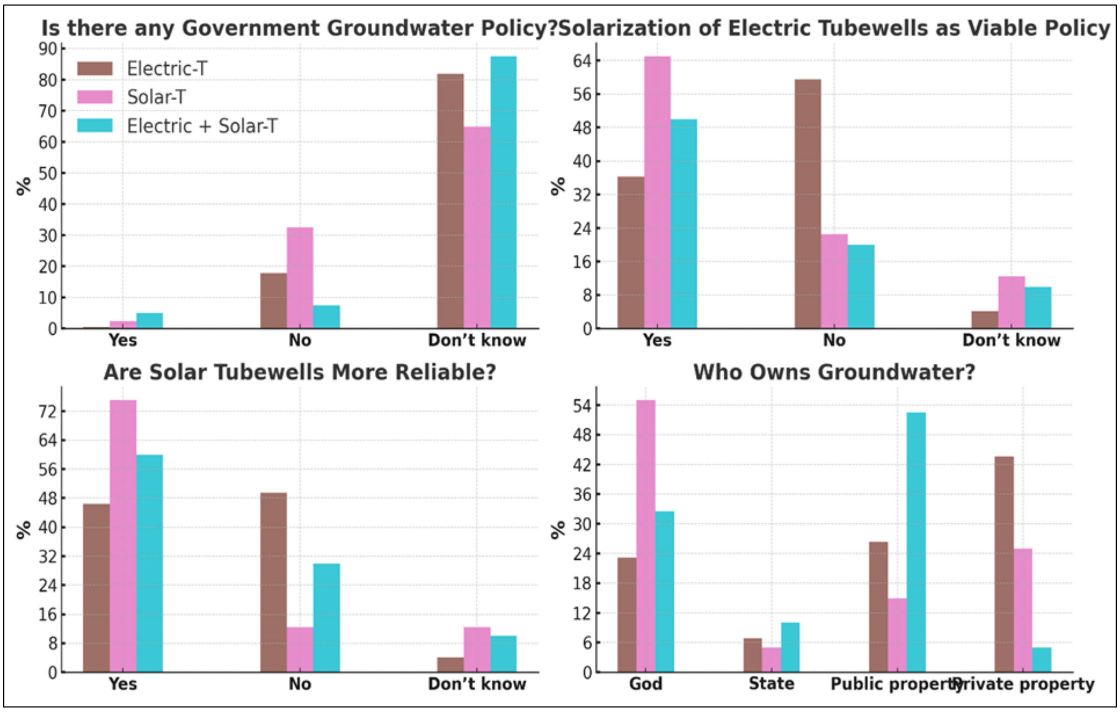

Fig. 5: Perception of the respondents of three groups about groundwater-related policies. Source: Field survey, 2023.

Citation: Ameenullah, Dabiah, A.T., Ullah, R., Khair, S.M., Agha, S.S., Khan, R., Muddassir, M. & Boye, M. (2026). Solarization and groundwater depletion: the hidden costs of solar-powered agriculture in Balochistan, Pakistan. Agrobiological Records, 25, 242-256. https://doi.org/10.47278/journal.abr/2026.060

Table 3 presents an examination of socio-economic variables distinguishing solar and electric tubewell users, revealing significant disparities that underscore potential effects on groundwater depletion in Highland Balochistan. Users of solar tubewells are generally younger and more educated than their peers, suggesting greater receptiveness to adopting innovative technologies. Notably, although solar tubewell users possess greater average farm sizes (43.76 acres), they cultivate less land (11.32 acres) compared to electric tubewell users, who cultivate an average of 15.47 acres. Both groups, however, contain significant expanses of unproductive land, with solar users averaging 19.88 acres.

This raises concern that solar tubewells, by offering cheaper, more accessible energy, may induce farmers to expand crop production, leading to increased water extraction. Although solar tubewells reduce reliance on electricity and provide a more sustainable energy alternative, they may inadvertently exacerbate groundwater over-extraction, further depleting aquifers.

Table 3: Socioeconomic characteristics of the respondents

Socio-economic variables	Solar tubewell users (N=100)				Electric tubewells farmer (N=220)			
	Mean	Std. Dev.	Min	Max	Mean	Std. Dev.	Min	Max
Age (years)	43.72	10.53	29.12	64.00	45.00	12.17	24.00	82.00
Schooling(years)	7.77	5.18	3.00	16.00	5.80	4.18	0.00	16.00
Family size (no.)	17.00	10.92	5.00	44.00	19.52	13.37	3.00	59.00
Farm size (acres)	43.76	55.79	5.00	210.00	34.82	32.27	5.00	231.00
Cultivated land (acres)	11.32	12.89	3.00	55.00	15.47	14.90	4.00	121.00
Barren land (acres)	19.88	25.20	2.00	109.00	22.96	27.24	3.00	199.00

This paradox, in which a sustainable energy solution exacerbates environmental degradation, presents a significant barrier to long-term agricultural viability in the region.

3.3. Econometric Estimation

Table 4 presents the logistic regression results, elucidating the factors that influence groundwater depletion in relation to solarized tubewells. Whereas the descriptive analyses draw on the full sample of 320 valid respondents, the logistic regression was estimated on 319 observations because one case with a missing value on an explanatory variable was removed through listwise deletion; this exclusion does not materially affect the estimates. The most notable finding is a positive, statistically significant correlation between tubewell solarization and groundwater depletion ($\beta = 3.143$, $P<0.01$). This confirms the study's first hypothesis (H1): whereas solarizing tubewells reduces energy costs, it unintentionally promotes excessive water consumption, leading to greater groundwater depletion. Solarization may give the impression of "free water" as energy costs are reduced, encouraging excessive extraction. Furthermore, age shows a positive correlation with groundwater depletion ($\beta = 0.057$, $P<0.01$), indicating that older farmers, perhaps due to their established agricultural techniques and reliance on irrigation, are more likely to contribute to depletion, lending support to H2.

Older farmers may resist the adoption of water-conserving technologies or alternative irrigation methods, leading to increased water consumption. Although schooling shows a positive, albeit small, correlation ($\beta = 0.047$, $p = 0.125$), this suggests that education, in this context, does not significantly affect groundwater use habits. Schooling, although typically associated with improved decision-making, may not immediately affect irrigation or water management practices in this agricultural context. Cultivated land shows a negative correlation with groundwater depletion ($\beta = -0.103$, $P<0.01$), suggesting that farmers with larger landholdings are more likely to manage water resources more sustainably, perhaps due to economies of scale or superior irrigation methods. More extensive agricultural operations may prioritize the conservation of groundwater resources to sustain productivity, thereby elucidating the inverse correlation.

The depth of the water table exerts a positive and significant influence on depletion ($\beta = 0.004$, $P<0.01$), suggesting that deeper water tables require more extensive extraction, leading to overexploitation. Farmers must increase water extraction when water levels decline, exacerbating depletion. The frequency of irrigation is a crucial factor in depletion ($\beta = 1.768$, $P<0.01$), reinforcing the idea that frequent irrigation intensifies groundwater overexploitation. Frequent irrigation indicates inefficient water use or the cultivation of high-water-demand crops, thereby exacerbating strain on water supplies. Finally, the utilization of high-efficiency irrigation systems shows a negative correlation with depletion ($\beta = -0.695$), although this association is not statistically significant ($p = 0.159$), providing only partial support for H3. This indicates that although these technologies may reduce water use, their impact is insufficient to offset the consequences of increased tubewell utilization. Farmers may implement high-efficiency systems for reasons beyond water conservation, such as labour reduction or convenience, thereby diminishing the anticipated environmental benefits.

The data indicate that solarization, although advantageous for reducing energy consumption, results in unforeseen environmental repercussions by increasing water use, thereby exacerbating groundwater depletion. This highlights the need for comprehensive policies that promote energy efficiency and sustainable water management.

Citation: Ameenullah, Dabiah, A.T., Ullah, R., Khair, S.M., Agha, S.S., Khan, R., Muddassir, M. & Boye, M. (2026). Solarization and groundwater depletion: the hidden costs of solar-powered agriculture in Balochistan, Pakistan. Agrobiological Records, 25, 242-256. https://doi.org/10.47278/journal.abr/2026.060

Table 4: Logistic estimates of different factors contributing to groundwater depletion (N = 319)

Explanatory variables	Coef.	SE/	t-value	P-value	95% coeff	Interval]	Sig
Adoption of solarization of tubewells (0=no, 1=yes)	3.143	0.577	5.45	0	2.012	4.274	***
Age (year)	0.057	0.015	3.75	0	0.027	0.087	***
Schooling (year)	0.047	0.031	1.53	00.125	-0.013	0.107	
Cultivated land (acre)	-0.103	0.024	-4.30	0	-0.15	-0.056	***
Watertable depth nowadays (feet)	0.004	0.001	5.13	0	0.002	0.005	***
Irrigation frequency (numbers)	1.768	0.448	3.95	0	0.89	2.646	***
Use of High-efficiency irrigation system (0=no, 1=yes)	-0.695	0.494	-1.41	.159	-1.664	0.273	
Constant	-4.103	0.902	-4.55	0	-5.871	-2.334	***
Mean dependent var	0.545		SD dependent var		0.499		
Pseudo r-squared	0.385		Number of obs		319		
Chi-square	169.428		Prob > chi2		0.000		
Akaike crit. (AIC)	286.160		Bayesian crit. (BIC)		316.281		

*** P<0.01, ** P<0.05.

Source: Field survey, 2023.

4. DISCUSSION

The central finding of this study – that solarization of tubewells is the strongest predictor of groundwater depletion in Highland Balochistan (β = 3.143, P<0.01) – provides province-level empirical support for what has recently been characterized as the global "solar irrigation paradox." Because sunlight is free at the point of use, solar pumping reduces the marginal cost of groundwater extraction to nearly zero, thereby removing the last remaining economic brake on over-pumping. This mechanism has now been documented across low- and middle-income countries, where behavioural evidence shows that farmers respond to zero-cost energy by irrigating longer, expanding cultivated area or selling water, unless extraction is checked by regulation or counter-incentives (Balasubramanya et al., 2024). Our results align closely with empirical findings from Rajasthan, India, where solar-pump adopters significantly increased groundwater extraction relative to comparable non-adopters (Gupta, 2019), and with the warning of Shah et al. (2018a; 2018b) that South Asia's rapidly multiplying solar pumps could destabilize the region's energy–groundwater nexus. They also corroborate recent evidence from Balochistan itself, where the shift from conventional to solar tubewells has been associated with intensified aquifer stress (Khan et al., 2025), and from the Kashmir Valley, where solar-powered irrigation improved farm performance but simultaneously increased water application (Peer et al., 2026). Viewed against this literature, Balochistan's flagship programme to solarize approximately 28,000 tubewells (DAWN, 2024) risks converting an energy-subsidy problem into a far less reversible water-depletion problem unless extraction safeguards are embedded in its design from the outset (Shah, 2022; Sadiq et al., 2025).

The perception results deepen this concern by revealing a pronounced governance vacuum. More than four-fifths of electric tubewell users and a comparable share of mixed users were unaware of any groundwater-related policy, echoing the national diagnosis that Pakistan has pursued colossal development of groundwater while neglecting its management (Qureshi, 2020) and that institutional gaps persist at every tier of water governance (Ahmad et al., 2023; Prabhakarsriram et al., 2026). Equally consequential are the prevailing ownership norms: a majority of solar users regarded groundwater as divinely owned, while many electric users considered it private property attached to their land. Where a common-pool resource is perceived either as God-given or as a private attribute of landholding, individual restraint is unlikely to emerge spontaneously, and the classic tragedy of the commons unfolds (Nagaraj et al., 1999). These socio-cultural findings imply that regulatory instruments will only be effective if they are accompanied by sustained awareness campaigns and are framed in ways that local communities regard as socially and religiously legitimate.

The socioeconomic determinants identified by the model are likewise consistent with the wider literature. The positive effect of age suggests that older farmers, habituated to traditional flood irrigation and decades of subsidized pumping, adjust their extraction behaviour more slowly – a pattern repeatedly observed in technology-adoption studies within Pakistan's groundwater economies (Watto & Mugera, 2016; Qureshi et al., 2022; Rauf et al., 2025). The statistical insignificance of schooling indicates that generic education does not automatically translate into water-conserving practice in the absence of targeted extension services and water literacy, mirroring findings on irrigation efficiency elsewhere in the developing world (Wudil et al., 2023). The negative association between cultivated area and depletion implies that larger operators, who face higher aggregate pumping costs and enjoy better access to information and capital, manage water more strategically, whereas smallholders irrigate limited plots intensively – a distributional insight with direct relevance for targeting conservation programmes toward small and marginal farmers.

Perhaps the most policy-relevant result is the statistical insignificance of high-efficiency irrigation systems. Although HEIS carries the expected negative sign, its adoption alone has not measurably restrained depletion. This

Citation: Ameenullah, Dabiah, A.T., Ullah, R., Khair, S.M., Agha, S.S., Khan, R., Muddassir, M. & Boye, M. (2026). Solarization and groundwater depletion: the hidden costs of solar-powered agriculture in Balochistan, Pakistan. Agrobiological Records, 25, 242-256. https://doi.org/10.47278/journal.abr/2026.060

is fully consistent with the international "paradox of irrigation efficiency," whereby field-scale efficiency gains are re-absorbed through expanded irrigated area or intensified cropping, so that basin-scale water consumption rarely falls unless withdrawals are simultaneously capped (Grafton et al., 2018; Gondal, 2025). For Balochistan, the implication is unambiguous: subsidizing drip or sprinkler systems as a stand-alone accompaniment to solarization will not protect the aquifers; efficiency incentives must be bundled with enforceable extraction limits, metering of solar wells and basin-level water accounting.

These findings carry direct implications for groundwater conservation, policy design, irrigation efficiency and climate resilience. First, solarization should be made conditional: conversion of a tubewell should require mandatory HEIS installation, a capped pump capacity proportional to landholding, and grid connection with net-metering so that farmers can sell surplus solar power on non-irrigation days, thereby restoring a positive opportunity cost to every hour of pumping – an incentive architecture whose promise has been demonstrated by solar-power buy-back pilots in South Asia (Shah et al., 2018a; 2018b; Shah, 2022). Second, the regulatory framework requires urgent modernization: revising the Balochistan Ground Water Rights Administration Ordinance, empowering a provincial groundwater regulatory authority and instituting participatory basin-level monitoring would convert the current open-access regime into a managed commons (Qureshi, 2020; Ahmad et al., 2023). Third, because shallow wells are globally the first casualties of declining water tables (Jasechko & Perrone, 2021; Razzaq et al., 2025), protecting the shallow aquifers on which marginal farmers and drinking-water supplies depend must be an explicit distributional objective, complemented by managed aquifer recharge and rehabilitation of the traditional karez systems (Ashraf, 2020). Finally, under a warming and increasingly drought-prone climate with annual rainfall of only 200–300 mm, unregulated depletion would progressively erode cropping intensity, food security and rural livelihoods (Hanjra & Qureshi, 2010; Jain et al., 2021); coupling solar energy with disciplined water-demand management is therefore not merely an environmental preference but a precondition of climate-resilient agriculture in Balochistan.

This study has limitations that frame an agenda for future research. It relies on cross-sectional, self-reported perception data from three basins of a single province, and the dependent variable captures perceived rather than piezometrically measured depletion. Future research should triangulate farmer perceptions with long-term piezometric records and satellite-based estimates of groundwater storage, exploit panel data to identify the causal effect of solarization as the provincial program is rolled out, and evaluate pilot schemes that combine solar conversion with metering, extraction quotas, and net-metering. Notwithstanding these limitations, the convergence of the econometric results, farmers' own perceptions and the international evidence base lends considerable confidence to the study's central conclusion.

5. CONCLUSION

This study investigated the impact of tubewell solarization in Highland Balochistan, focusing on the paradox of resolving electricity shortages while intensifying groundwater depletion. Solar-powered tubewells are increasingly used to reduce dependence on conventional energy sources, especially in rural communities where the electricity supply is intermittent. While solarization provides a cost-effective and sustainable energy option, the study found that it has unanticipated environmental impacts, including over-extraction of groundwater. The deployment of solar tubewells is significantly associated with increasing groundwater depletion ($\beta = 3.143$, $P<0.01$). The lower energy costs associated with solarization encourage farmers to draw more water, treating it as a less expensive resource, hastening the loss of already-stressed groundwater sources. While solarization addresses electricity concerns, it unintentionally exacerbates groundwater loss, posing a substantial risk to agricultural sustainability in the region. The study advocates immediate policy action to integrate energy efficiency with sustainable water management. Without effective control, the environmental benefits of solar energy will be outweighed by the rapid loss of crucial groundwater resources, jeopardizing the long-term viability of agriculture in Balochistan.

Recommendations

To promote sustainable groundwater, use in Balochistan, solarization of tube wells should be supplemented with high-efficiency irrigation systems (HEIS). This requirement would promote water conservation by limiting groundwater withdrawals and addressing over-extraction from unregulated solar-powered wells. Furthermore, incorporating a net-metering option for solar-powered wells would allow farmers to sell excess energy back to the national grid on non-irrigation days, providing a financial incentive to conserve water. This program would improve water efficiency by raising the opportunity cost of over-pumping, encouraging farmers to prioritize irrigation efficiency.

To support sustainable irrigation, additional measures include promoting drought-resistant, low-delta, high-value crops; lowering agricultural water demand; and enhancing water literacy and on-farm water management. Strengthening water governance, such as revising the Balochistan Ground Water Rights Administration Ordinance (BGWRA) and establishing a Balochistan Groundwater Regulatory Authority, would provide the regulatory framework required to protect aquifers and ensure effective water resource management for long-term sustainability.

ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
Open Access Journal

Declarations

Funding: This study didn't receive any funding from any agencies in the public, commercial, or non-profit sector.

Acknowledgement: The authors would like to acknowledge their respective institutions for providing academic support.

Conflicts of Interest: Authors have no conflicts of interest.

Data Availability: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Ethics Statement: This work involved human data. The work was approved by the Institute of Agricultural and Resource Economics, Faculty of Social Sciences, University of Agriculture Faisalabad.

Author's Contributions: Ameenullah: conceptualization, study design, field data collection and drafting of the original manuscript. Abdulaziz Thabet Dabiah: supervision, validation and critical revision of the manuscript. Raza Ullah: supervision, econometric analysis and interpretation of the results. Syed Muhammad Khair: Reviewing and Writing, survey instrument design and field validation. Syed Sadiq Agha: Reviewing and Writing and value-chain contextualization. Rizwan Khan: Reviewing and Writing, data curation and descriptive analysis. Muhammad Muddassir: methodology, review, editing and correspondence. Mortala Boye: Reviewing, editing and Writing. All authors have read and approved the final version of the manuscript

Generative AI Statements: The authors declare that no Gen AI/DeepSeek was used in the writing/creation of this manuscript.

Publisher's Note: All claims stated in this article are exclusively those of the authors and do not necessarily represent those of their affiliated organizations or those of the publisher, the editors, and the reviewers. Any product that may be evaluated/assessed in this article or claimed by its manufacturer is not guaranteed or endorsed by the publisher/editors.

REFERENCES

Ahmad, M., Mustafa, U., & Iqbal, M. (2023). Groundwater governance and smallholder agriculture in Pakistan: Institutional gaps and reform pathways. Water Policy, 25(2), 310–328. https://doi.org/10.2166/wp.2023.004
Ahmad, S. (2006). Issues restricting capping of tube well subsidy and strategy for introducing the smart subsidy in Balochistan. Water for Balochistan Policy Briefings, 2.
Aidoo, R., Mensah, J. O., & Tuffour, T. (2013). Determinants of household food security in the Sekyere-Afram plains district of Ghana. European Scientific Journal, 9(21), 514–521.
Ali, M. A., Yamin, M., Arslan, C., Farid, U., & Nasir, A. (2020). A feasibility study: Off-grid photovoltaic solar power supply to the remote areas of Pakistan. Pakistan Journal of Agricultural Sciences, 57(5), 1313–1316. https://doi.org/10.21162/PAKJAS/20.468
Ashraf, M. (2020). Groundwater management in Balochistan, Pakistan: A case study of Karez rehabilitation. AGRIS. https://agris.fao.org/search/en/providers/122582/records/647481f9bf943c8c7988a522
Balasubramanya, S., Garrick, D., Brozović, N., Ringler, C., Zaveri, E., Rodella, A.-S., Buisson, M.-C., Schmitter, P., Durga, N., Kishore, A., Minh, T. T., Kafle, K., Stifel, D., Balasubramanya, S., Chandra, A., & Hope, L. (2024). Risks from solar-powered groundwater irrigation. Science, 383(6680), 256–258. https://doi.org/10.1126/science.adi9497
Banerjee, S., & Martin, S. W. (2009). A binary logit analysis of factors impacting adoption of genetically modified cotton. African Journal of Agricultural Research, 4(12), 1445–1451.
Choudhary, M. A., Lodhi, A. S., Ahmad, M., & Ahmed, M. (2008). A comparative study of cost of production and decision making analysis in case of onion and sunflower crops in Quetta district. Sarhad Journal of Agriculture, 24(3), 469–478.
Closas, A., & Rap, E. (2017). Solar-based groundwater pumping for irrigation: Sustainability, policies, and limitations. Energy Policy, 104, 33–37. https://doi.org/10.1016/j.enpol.2017.01.035
DAWN (2024). Accord signed to 'solarise' tube wells in Balochistan. DAWN Newspaper. https://www.dawn.com/news/1844774
Gondal, I. A. (2025). Low-speed wind energy devices to facilitate nearly zero energy buildings in urban Pakistan. Proceedings of the Institution of Civil Engineers-Energy, 178(1), 16-33. https://doi.org/10.1680/jener.23.00002
Government of Balochistan (GOB) (2021–22). Agriculture statistics of Balochistan. Department of Agriculture Extension.
Grafton, R. Q., Williams, J., Perry, C., Molle, F., Ringler, C., Steduto, P., Udall, B., Wheeler, S. A., Wang, Y., Garrick, D., & Allen, R. G. (2018). The paradox of irrigation efficiency. Science, 361(6404), 748–750. https://doi.org/10.1126/science.aat9314
Gupta, E. (2019). The impact of solar water pumps on energy-water-food nexus: Evidence from Rajasthan, India. Energy Policy, 129, 598–609. https://doi.org/10.1016/j.enpol.2019.02.008

Hair, J. F., Tatham, R. L., Anderson, R. E., & Black, W. C. (1998). Multivariate data analysis (5th ed.). Prentice Hall.
Halcrow-Pakistan & Cameos Consultants (2008). Identification of recharge potential zones in three over-drawn basins (PLB, Nari, and Zhob): Final report. Irrigation and Power Department, Government of Balochistan; Royal Government of the Netherlands.
Hanjra, M. A., & Qureshi, M. E. (2010). Global water crisis and future food security in an era of climate change. Food Policy, 35(5), 365–377. https://doi.org/10.1016/j.foodpol.2010.05.006
Irfan, M., Zhao, Z. Y., Ahmad, M., & Mukeshimana, M. C. (2019). Solar energy development in Pakistan: Barriers and policy recommendations. Sustainability, 11(5), 1206. https://doi.org/10.3390/su11051206
IUCN (2000). Balochistan conservation strategy. IUCN Pakistan & Government of Balochistan.
Jain, M., Fishman, R., Mondal, P., Galford, G. L., Bhattarai, N., Naeem, S., Lall, U., Balwinder-Singh, & DeFries, R. S. (2021). Groundwater depletion will reduce cropping intensity in India. Science Advances, 7(9), eabd2849. https://doi.org/10.1126/sciadv.abd2849
Jasechko, S., & Perrone, D. (2021). Global groundwater wells at risk of running dry. Science, 372(6540), 418–421. https://doi.org/10.1126/science.abc2755
Khair, S. M., Culas, R. J., & Hafeez, M. (2012). Groundwater markets under the water scarcity and declining watertable conditions: The upland Balochistan region of Pakistan. Agricultural Systems, 107, 21–32. https://doi.org/10.1016/j.agsy.2011.11.007
Khair, S. M., Rasheed, A., & Culas, R. (2021). Improving groundwater management to enhance agriculture and farming livelihoods: Socio-economic analysis of groundwater resource management for Balochistan, Pakistan (ILWS Report No. 155). Institute for Land, Water and Society, Charles Sturt University, Albury, NSW 2640, Australia. https://cdn.csu.edu.au/__data/assets/pdf_file/0004/4338886/ILWS-Report-155-Socio-Economic-Analysis-of-Groundwater-Resource-Management-for-Balochistan,-Pakistann.pdf
Khan, A., Ahmed, I., & Khair, S. M. (2025). Sustainable irrigation: A shift from conventional to solar tube-wells. Groundwater, 63(3), 326–334. https://doi.org/10.1111/gwat.13469
Lefore, N., Closas, A., & Schmitter, P. (2021). Solar for all: A framework to deliver inclusive and environmentally sustainable solar irrigation for smallholder agriculture. Energy Policy, 154, 112313. https://doi.org/10.1016/j.enpol.2021.112313
Louangrath, P. (2018). Reliability and validity of survey scales. International Journal of Research & Methodology in Social Science, 4(3), 50–62.
Maxwell, J. A. (2013). Qualitative research design: An interactive approach (3rd ed.). SAGE Publications.
Mustafa, Z., Iqbal, R., Siraj, M., & Hussain, I. (2022). Cost–benefit analysis of solar photovoltaic energy system in agriculture sector of Quetta, Pakistan. Environmental Sciences Proceedings, 23(1), 26. https://doi.org/10.3390/environsciproc2022023026
Nagaraj, N., Frasier, W. M., & Sampath, R. K. (1999). Groundwater institutions in US and India: Sustainable and equitable resource use. Economic and Political Weekly, 34(26), A93–A104.
Peer, Q. J. A., Rashid, I., Tabina, K., Sadaf, S., Iqra, A., & Para, I. A. (2026). Solar-powered irrigation and farm performance: An impact evaluation from Kashmir Valley, India. Indian Journal of Extension Education, 62(2), 59–65. https://doi.org/10.48165/IJEE.2026.62210
Prabhakarsriram, A., Manimuthu, S., Ariputhiran, A., Kadar, M. I. A., Arumugam, J., & Gandhi, S. (2026). Social Life Cycle Assessment of Irrigation Technologies in Indian Cassava Farming. Indian Journal of Extension Education, 62(3), 260-266. https://doi.org/10.48165/IJEE.2026.62339
Qamar, S. H., Hanak, D. P., Ali, M., Gomes, J., & Khan, K. Z. (2024). Design, modeling and cost analysis of 8.79 MW solar photovoltaic power plant at National University of Sciences and Technology (NUST), Islamabad, Pakistan. Scientific Reports, 14. https://doi.org/10.1038/s41598-024-74187-w
Qureshi, A. S. (2020). Groundwater governance in Pakistan: From colossal development to neglected management. Water, 12(11), 3017. https://doi.org/10.3390/w12113017
Qureshi, A. S., Gill, M. A., & Sarwar, A. (2008). Sustainable groundwater management in Pakistan: Challenges and opportunities. Irrigation and Drainage, 57(3), 373–388. https://doi.org/10.1002/ird.400
Qureshi, A. S., Shah, T., & Akhtar, M. (2022). The groundwater economy of Pakistan: Challenges and prospects for sustainable management. Hydrogeology Journal, 30(4), 1145–1161. https://doi.org/10.1007/s10040-022-02451-2
Rafi-Khan, D., & Maria, M. (2023). Scarcity of water in Quetta–a way forward. Journal of Positive School Psychology, 7(2), 1–10. https://journalppw.com
Rana, A. W., Davies, S., Moeen, M. S., Shikoh, S. H., & Rizwan, N. (2020). Solarization of electric tube-wells for agriculture in Balochistan: Economic and environmental viability. International Food Policy Research Institute (IFPRI). https://doi.org/10.2499/p15738coll2.134030
Rauf, Q., Li, Y., & Ashraf, A. (2025). Sustainable Agriculture in Balochistan. In: 2nd EAI International Conference on Renewable Energy and Sustainable Manufacturing: ICRESM 2024 (p. 155). Springer Nature. https://doi.org/10.1007/978-3-031-90629-9
Razzaq, A., Liu, H., & Yang, D. (2025). Groundwater markets at a crossroads: A review of energy transitions, digital innovations, and policy pathways. Water, 17(14), 2079. https://doi.org/10.3390/w17142079
Rizwan, N., Shikoh, S. H., Davies, S., Moeen, M. S., Rana, A. W., & Haider, Z. (2021). Assessing the economic cost of depleting groundwater in Balochistan: A social accounting matrix (SAM) multiplier approach (IFPRI Discussion Paper). International Food Policy Research Institute. https://doi.org/10.2499/p15738coll2.134349
Sadiq, S. M., Singh, I. P., Ahmad, M. M., & Abdulmumin, S. (2025). Agrifusion of Water and Status, Management, and Challenges Wastewater Technologies: Status, Management, and Challenges. In Sustainable Use of Wastewater in Agriculture (pp. 85-121). Apple Academic Press. https://doi.org/10.1201/9781003610694

ISSN: 2708-7182 (Print); ISSN: 2708-7190 (Online)
Open Access Journal

Sanni, S. A., & Doppler, W. (2007). Socio-economic determinants of household fertilizer use intensity for maize-based production systems in the Northern Guinea Savannah of Nigeria. Journal of Applied Sciences, 7(12), 1774–1779.

Saunders, M., Lewis, P., & Thornhill, A. (2015). Research methods for business students (7th Ed). Pearson Education.

Shah, S. A. A., & Solangi, Y. A. (2019). A sustainable solution for electricity crisis in Pakistan: Opportunities, barriers, and policy implications for 100% renewable energy. Environmental Science and Pollution Research, 26(29), 29687–29703. https://doi.org/10.1007/s11356-019-05995 -3

Shah, S. A. A., Valasai, G. D., Memon, A. A., Laghari, A. N., Jalbani, N. B., & Strait, J. L. (2018a). Techno-economic analysis of solar PV electricity supply to rural areas of Balochistan, Pakistan. Energies, 11(7), 1777. https://doi.org/10.3390/en11071777

Shah, T., Rajan, A., Rai, G. P., Verma, S., & Durga, N. (2018b). Solar pumps and South Asia's energy-groundwater nexus: Exploring implications and reimagining its future. Environmental Research Letters, 13(11), 115003. https://doi.org/10.1088/1748-9326/aae53f

Shah, T. (2022). Solar irrigation pumps and groundwater depletion: Reframing the debate. Nature Sustainability, 5(7), 562–564. https://doi.org/10.1038/s41893-022-00896-3

Wakeel, M., Chen, B., & Jahangir, S. (2016). Overview of energy portfolio in Pakistan. Energy Procedia, 88, 71–75. https://doi.org/10.1016/j.egypro.2016.06.010

WAPDA. (1993). Groundwater resources of Balochistan Province, Pakistan. Directorate General Hydrology. Water and Power Development Authority (WAPDA).

Watto, M. A., & Mugera, A. W. (2016). Groundwater depletion in the Indus Plain of Pakistan: Imperatives, repercussions and management issues. International Journal of River Basin Management, 14(4), 447–458. https://doi.org/10.1080/15715124.2016.1204474

Wudil, A. H., Ali, A., Mushtaq, K., Baig, S. A., Radulescu, M., Prus, P., Usman, M., & Vasa, L. (2023). Water use efficiency and productivity of irrigated rice cultivation in Nigeria: An application of the stochastic frontier approach. Sustainability, 15(10), 7824. https://doi.org/10.3390/su15107824

Yamane, T. (1967). Statistics: An introductory analysis (2nd Ed). Harper & Row.

Yaqoob, H., Teoh, Y. H., Din, Z. U., Sabah, N. U., Jamil, M. A., Mujtaba, M., & Abid, A. (2021). The potential of sustainable biogas production from biomass waste for power generation in Pakistan. Journal of Cleaner Production, 307, 127250. https://doi.org/10.1016/j.jclepro.2021.127250

Citation: Ameenullah, Dabiah, A.T., Ullah, R., Khair, S.M., Agha, S.S., Khan, R., Muddassir, M. & Boye, M. (2026). Solarization and groundwater depletion: the hidden costs of solar-powered agriculture in Balochistan, Pakistan. Agrobiological Records, 25, 242-256. https://doi.org/10.47278/journal.abr/2026.060