Impacts of Solar-Powered Irrigation on Groundwater and Crop Yield: A Case Study of Kurram District, Pakistan

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Abstract

Farmers are rapidly transitioning from traditional to solar-powered irrigation systems (SPIS). A comprehensive study is needed to evaluate the advantages and disadvantages of SPIS. This study builds on previous research and incorporates field data collected in 2019 and 2024. In the Kurram district, crops are irrigated using both surface and groundwater resources. For this research, 54 tubewells solarized by the Directorate General of Agricultural Engineering, Khyber Pakhtunkhwa, were selected. Data on water table levels, discharge rates, and variations in crop yield were collected before (2019) and after (2024) the installation of SPIS. Water table declination was observed at six locations, while a rise in the water table was noted at two locations. The discharge rate of all tubewells remained consistent at approximately 5,000 gallons per hour (mph). Following the installation of SPIS, both the cropping area and yield per unit area increased significantly. The study found that farmers can recover their investment in SPIS, including costs for pumps, PV panels, inverters, and manually rotating structures, within 1.1 to 1.4 years. The government and policymakers should consider implementing policies and incentives to promote the widespread adoption of solar energy in agriculture. It is recommended that solar energy be utilized to power high-efficiency irrigation systems (HEIS), with an urgent focus on capacity building among farmers, advisors, and system installers to ensure sustainable water resource management. Furthermore, the adoption of SPIS can enhance crop yields, contributing to food security and poverty reduction.

Keywords: Solar, Power, Irrigation, Tubewell, Variation, SPIS

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Introduction

Agriculture employs 40% of the world's population, yet many farmers live in poverty (United Nations, 2015). Sustainable agriculture relies heavily on regular irrigation, which enhances yields, reduces vulnerability to erratic rainfall patterns, and enables diverse farming strategies (FAO, 2011). Irrigation is widely recognized as a critical driver of food security, income generation, job creation, and rural development (Besser et al., 2021). However, energy remains a vital component of irrigation services, and access to both water and power is often inconsistent for rural farmers (Hartung and Pluschke, 2018). While efficient water delivery systems minimize waste, the energy required for pumping water can be prohibitively expensive, particularly for smallholder farmers (Bashir et al., 2020).

Solar energy, one of the most potent renewable energy sources, offers a sustainable solution to this challenge. The sun provides an average of 1,000 watts per square meter (m^2) of energy per hour, which can be harnessed through photovoltaic (PV) systems to generate electricity for irrigation (Burney et al., 2010). Solar-powered irrigation systems (SPIS) have emerged as a reliable and cost-effective alternative to traditional diesel and electric pumps, offering farmers improved water-use efficiency, energy efficiency, and significant cost savings (Closas & Rap, 2017). Studies have shown that solar-powered tube wells are a practical investment with a short payback period. For instance, a cost-volume-profit analysis comparing solar-powered and diesel-operated tube wells revealed a capital recovery period of 1.42 years and an internal rate of return (IRR) of 36% (Bukhari et al., 2023).

The potential of SPIS has been recognized globally. In 2015, the Food and Agriculture Organization (FAO) and the Deutsche Gesellschaft für International Zusammenarbeit (GIZ) GmbH organized a workshop to explore the role of SPIS in agriculture, particularly in developing nations. Representatives from 19 countries shared their experiences with solar pumping technology, highlighting its applications in diverse contexts, from small-scale vegetable gardens to large-scale orchards and livestock watering systems (Hartung and Pluschke, 2018). Despite its benefits, SPIS faces challenges such as high initial costs, maintenance requirements, limited availability of replacement parts, and a lack of technical expertise and regulatory frameworks. A significant concern is the potential for over-extraction of groundwater, which underscores the need for effective management practices and policies to ensure sustainable use (Hussain et al., 2023).

Agriculture accounts for approximately 93% of the country's water usage in Pakistan, yet water-use efficiency remains low at around 40% (Iqbal et al., 2020). Groundwater is the primary source of water for agriculture, contributing to more than 60% of irrigation needs, as well as over 90% of domestic and nearly 100% of industrial water supplies (Bakhsh et al., 2016). The expansion of tube wells has played a pivotal role in agricultural growth, with groundwater use increasing from 31.6 billion cubic meters (BCM) in 1976 to 59.95 BCM in 2012 (FODP, 2012). However, the majority of these tube wells are diesel-powered, contributing to significant CO_2 emissions, estimated at 5.025 million metric tons annually (FAO, 2019). Replacing diesel pumps with solar-powered systems could drastically reduce these emissions while providing a sustainable energy source for irrigation (Guta et al., 2017).

Pakistan faces significant challenges in managing its water resources, exacerbated by climate change, population growth, and inefficient water-use practices. The Indus River system, the backbone of the country's water resources, is under increasing strain (Shakoor and Ejaz, 2019). Groundwater depletion is a growing concern, with withdrawal rates exceeding recharge rates in both urban and agricultural areas (Khan et al., 2021). In this context, solar-powered irrigation systems have emerged as a promising alternative to traditional diesel and electric pumps. However, the rapid adoption of SPIS raises concerns about the overexploitation of groundwater, particularly in the absence of robust regulatory frameworks and water management practices (Qureshi et al., 2010).

The Kurram district, located in Khyber Pakhtunkhwa, Pakistan, presents a unique case for studying the impact of SPIS on groundwater and crop yield. The district has vast fertile land, but much of it remains uncultivated due to water scarcity. Traditional irrigation systems, such as diesel and electric pumps, have had significant environmental and economic impacts, including groundwater depletion and high operational costs (Ali et al., 2019). In recent years, farmers in Kurram have increasingly adopted solar-powered tube wells, which have improved crop yields and expanded irrigated areas. However, the continuous operation of these systems raises concerns about aquifer sustainability and long-term groundwater availability.

This study examines the impact of solar-powered irrigation systems on groundwater levels and crop yields in the Kurram district. By analyzing data from 54 solar-powered tube wells, the research aims to provide insights into the benefits and challenges of SPIS adoption, with a focus on water table stability, discharge rates, and changes in agricultural productivity. The findings will contribute to the development of sustainable water management strategies and inform policies to balance agricultural productivity with groundwater conservation.

Research Methodology

Study Area

The research was conducted in the Kurram district, a newly merged district of Khyber Pakhtunkhwa, located in the northwest of Pakistan, with approximate coordinates of 33°53'29" N, 70°05'57" E, and an elevation of 5,663 feet. The district covers a total area of 3,380 square kilometers. Over 91% of Kurram's land is uncultivable, while only 8% of its total land area is cultivable (PARC, 2018). Cropped land constitutes approximately 12% of the land, with 27% of that area being cultivated more than once a year. Irrigation is primarily carried out through canals or tubewells. The major crops grown in the area include wheat, rice, beans, and groundnuts, among others. The soil types in Kurram district consist of hard and rocky plains, medium- and fine-textured piedmont alluvium, and calcareous soils. The locations of the selected tubewells are shown in Figure No. 1.

Figure 1. Solarized Tubewells Location

Data Collection

The research was conducted in the Kurram district, a newly merged district, to estimate the socio-economic impact and groundwater table variations resulting from the installation of solar-powered tubewells. Various types of data were collected for this purpose. The observed tube wells were installed by the Directorate General of Agricultural Engineering under the project titled "Culturable Waste Land Development and Solarization of Existing Agricultural Tubewells in Newly Merged Districts of Khyber Pakhtunkhwa." A total of 54 tubewells, installed between 2019 and 2022, were selected for this study. Data from the time of solar system installation (2019–2022) were collected from the office of the Agricultural Engineer in Kurram, while the presented data were gathered by the Assistant Agricultural Engineer of Kurram through site visits in March 2024. The data included water table depth, running time of the tubewells, energy sources used before solarization, and increases in crop yield. Figure No. 2 provides a field view of the installed Solar-Powered Irrigation Systems (SPIS).

Figure No. 2. View of Installed SPIS in Field

Discharge of Tubewells

The design discharge of each system was 5,000 gallons per hour (gph), and the present measured discharge was also approximately 5,000 gph. The discharge of the tubewells was measured using a bucket and a stopwatch. The mean sunshine hours in Pakistan range from 8 to 8.5 hours per day (Khalil et al., 2008). Assuming the tubewells operate for six months in a year, the expected discharge would be 7,200,000 gallons per year. While it is difficult to record the exact operating hours over the entire year, the above assumption is based on farmers' estimates.

Water Table Depth Measurement

Water table measurement is crucial for understanding variations in aquifers. The water table, defined as the upper surface of the saturated zone within an aquifer, can fluctuate due to various factors such as precipitation, groundwater pumping, and changes in surface water levels. Accurately monitoring and understanding the dynamics of groundwater systems are essential for effective water management. One key aspect of groundwater monitoring is measuring the water table, which provides insights into aquifer variations over time. By tracking the water table over time, researchers can gather valuable information about aquifer recharge and depletion patterns, which is vital for managing and sustainably utilizing this critical resource. In this study, the water tape method was used to measure the water table before solarization and the current water table levels of the tubewells.

Cropping data

The Kurram district has diverse soil types. The soil in the cultivable areas is predominantly calcareous and highly fertile. A variety of crops are cultivated in the district, including wheat, rice, beans, groundnuts, and various types of vegetables and fruits. For this research study, data were collected only for the major crops, namely wheat, rice, and beans. Farmers were individually interviewed for data collection. The data were collected in terms of the percentage increase in yield before and after solarization. Table No. 1 lists the tubewells where variations in the water table were observed.

Table 1. Water Table, Discharge, Crop Yield, and Energy Source for Tubewells Operation Before SPIS

S. No	Well Id	Standing water level Before solarization	After solarization	Cropped area (acres)	Variation in Water Table (ft)	remarks
1	Mr. Sabir Hussain	240ft	243	7	3	Increase
2	Mr. Zahir Hussain	180ft	184	6	4	Increase
3	Mr. Shujat Hussain	210ft	211	8	1	Increase
4	Mr. Ali	160ft	159	6	1	Decrease

	Ghulam					
5	Mr. Sajid Hussain	270ft	273	13	3	Increase
6	Mr. Qadam Ali	200ft	203	11	3	Increase
7	Mr. Ghayoor Ali	100ft	102	13	2	Increase
8	Mr. Mir Ali	130ft	128	10	2	Decrease
9	Mr. Meer Ahmad	90ft	88	8	2	Decrease

Energy source for tubewell operation

The tubewells in the study area were operated using different energy sources, primarily electricity and diesel fuel. Diesel-powered tube wells were more common than electric ones due to frequent electricity shortages. On average, a single diesel-powered tubewell consumed 8 liters of diesel per hour.

Results And Discussions

The results of this study are based on data related to the water table, discharge, crop yield, cropping area, and energy consumption of irrigation tubewells in the Kurram district. In this study, data from all 54 solar-powered tube wells—including water table levels, discharge rates, crop yield, and cropping area—were recorded and compared with historical data. Additionally, the energy consumption of tubewells before solarization was compared with the cost of solarization.

Variation in Discharge of Tubewells

The discharge of the tubewells was measured to estimate the total withdrawals from the aquifer. As per the design, the discharge of each tubewell was 5,000 gallons per hour (gph), and the practically measured discharge was also the same. For this research study, the discharge recorded in March 2024 was also consistent at 5,000 gph. The variation in discharge was found to be negligible. Farmers also confirmed that the discharge of the tubewells remained unchanged from the initial measurements. At this rate, each tubewell withdraws approximately 7,200,000 gallons per year if operated for eight hours daily over six months.

Variation in Water Table Depth After Solarization

The water table is one of the most important parameters in groundwater investigation studies. In this study, the water table in the Kurram district was found to be stable at most locations, with minor variations observed at some points. The water table in the area remained stable despite an annual discharge of 7,200,000 gallons per year from each tubewell. Additionally, there are many other tubewells in the study area installed by the irrigation department and private firms. The stability of the water table indicates that groundwater recharge exceeds withdrawal. The primary sources of groundwater recharge in the Kurram district are rainfall and snowfall from Koh-e-Sufaid. The soil in the district, particularly in upper Kurram, is calcareous and sandy, which enhances the infiltration rate. Figure No. 3 illustrates that the water table remained stable after the continuous operation of solar-powered tube-wells, except at nine points where minor changes were observed. The maximum decrease in water table depth was observed at tubewells no. 30, 50, and 53, as shown in Figure 3, with a decline of one to two feet. The previous water table depths at tubewells no. 30, 50, and 53 were 160, 130, and 90 feet, respectively, while the current depths are 159, 128, and 88 feet, respectively. An increase in water table depth was also observed at six points. The maximum increase was recorded at tubewell no. 33, with a rise of approximately 4 feet. The previous and current water table depths at tubewell no. 33 were 180 and 184 feet, respectively.

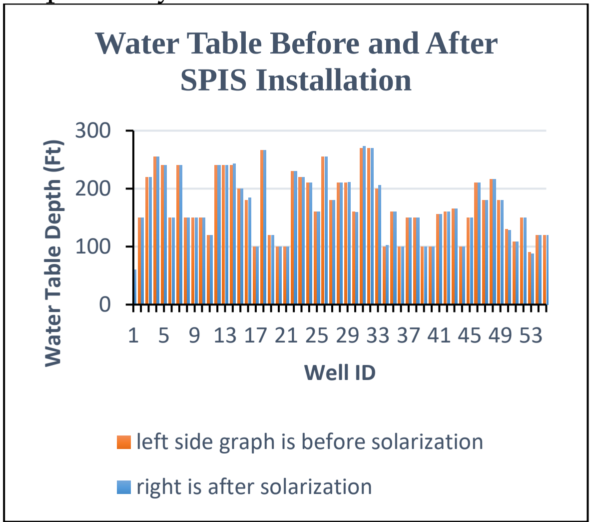

Figure 3: Water Table Variation Before and After Solar System Installation

Variation in cropping yield

The crops grown in an area depend on its climate. Crop yield is influenced by soil fertility and water availability under the same climatic conditions. The soil in Kurram is fertile, but most of the area is rainfed, which affects crop yield as farmers cannot irrigate their crops when needed and must rely on rainfall. A significant portion of the land in the Kurram district is cultivable but remains barren due to the unavailability of water. Groundwater is available in large quantities for irrigation in the district, but energy is required to extract and use it. Previously, most farmers grew crops primarily for their consumption, relying on diesel, electric, or other energy sources rather than solar energy. With the installation of Solar-Powered Irrigation Systems (SPIS), farmers began farming on a commercial scale, as it eliminated a major expense. A variety of crops, vegetables, and fruits are grown in the Kurram district. According to farmers, a significant increase in yield was observed for major crops such as wheat, rice, beans, maize, and tomatoes. After the installation of SPIS, both the yield per unit area and the cropping area increased. On average, the increase was noted to be about three times higher than before the installation of SPIS.

SPIS and diesel power-operated system cost analysis

The agricultural tubewells in the study area were primarily operated using diesel before the installation of Solar-Powered Irrigation Systems (SPIS). The installed pumps on these tube-wells were 25 hp turbine pumps, which consumed 8 liters of diesel per hour (lph) to achieve a discharge of 9,000 gallons per hour (gph). This data was collected experimentally at the site. Under the project, these diesel pumps were replaced with solar pumps, categorized into different capacities: 10 hp, 12 hp, and 15 hp, with design discharges ranging from 5,000 to 6,000 mph, depending on the water table in the area.

To estimate the yearly fuel cost for pumping 7,200,000 gallons using a diesel pump, it was calculated that a diesel pump would consume 6,400 liters of fuel annually, based on the consumption rate of 1,125 gallons per liter for the installed diesel pumps in the area. The cost of setting up 10 hp, 12 hp, and 15 hp solar systems was Rs. 1,900,000, Rs. 2,100,000, and Rs. 2,400,000, respectively. Under the project, SPIS was provided to farmers with an 80% subsidy.

The annual cost of operating diesel-powered tubewells to pump 7,200,000 gallons is Rs. 1,728,000, based on the consumption of 6,400 liters of diesel for Rs. 270 per liter (as of May 2024). This analysis shows that farmers can recover their investment in SPIS within just 1.1 to 1.4 years.

Conclusion And Recommendation

Pakistan is an agricultural country where most farmland is irrigated by canals and tubewells. Tubewells directly or indirectly irrigate 73% of the total irrigated area. Groundwater extraction in Pakistan is approximately 60 billion cubic meters (BCM), irrigating around 80 million hectares. Many tubewells in Pakistan are operated using electricity and diesel fuel, which has become increasingly problematic for farmers due to rising electricity and fuel costs. As a result, farmers are now shifting to Solar-Powered Irrigation Systems (SPIS) due to their zero running costs. The government has also introduced various subsidy schemes to promote SPIS, which is gaining rapid acceptance among the farmers.

SPIS has both positive and negative impacts, though the positive impacts outweigh the negative ones. However, the impact on groundwater resources is a significant concern. Farmers often extract water from aquifers continuously without considering long-term sustainability, which can lead to groundwater depletion over time.

In this study, the water table, discharge, and increase in crop yield were recorded for 54 tubewells. The water table and discharge in the area remained stable after three years of SPIS installation. A slight decline was observed at a few points, specifically in wells numbered 16, 14, 31, 33, and 34, but the discharge from these wells remained stable. The maximum increase in water table depth was observed at tubewell no. 33, with a rise of 4 feet. The Kurram district has significant potential for SPIS due to its vast barren fertile land and stable groundwater resources. The impact of SPIS on crop yield has been substantial, enabling farmers to cultivate and irrigate larger areas. Farming has now shifted to a commercial basis due to SPIS installation, with notable increases in the production of wheat, rice, and beans. SPIS is a reliable replacement for diesel and electric-powered irrigation systems. However, the adoption of SPIS has been gradual due to constraints such as lack of awareness, limited financial resources, and technical skills. The high initial cost of SPIS has been identified as the main barrier for farmers, particularly small landowners. To promote sustainable agriculture and improve energy access for farmers, the government and other stakeholders should collaborate to provide subsidies, financial assistance, and technical support for the purchase and installation of solar irrigation systems. Policymakers must also develop and implement effective management plans and regulations to prevent excessive groundwater abstraction by replacing diesel-powered pumps with solar pumps. For more efficient water use, SPIS should be integrated with high-efficiency irrigation systems. The adoption of solar tube-wells in the Kurram district is highly commendable and should be encouraged further.

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