KIGS Working Paper

The Effectiveness of On-Farm, Micro-catchment-based Rainwater Harvesting: Evidence from Rural Rajasthan, India

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Last updated: October 28, 2024

Abstract

This paper assesses the effectiveness of an on-farm, micro-catchment-system-based rainwater harvesting project in the state of Rajasthan, India that directs rainwater to open wells. It uses a mixed-method approach to assess the effectiveness of the project, including quantitative data analysis and a qualitative assessment through interviews with farmers. The water availability is measured on three metrics—the water level in the well, the amount of farmland irrigated, and the amount of time the engine could pump water daily. The paper finds a statistically significant improvement on all the metrics. The interviews with farmers corroborate these findings and provide further insights.

Keywords: SDG 13: Climate action; well recharge; rainwater harvesting; arid regions; Global South

Introduction

Communities globally are facing water scarcity, especially those located in arid and semi-arid regions. Population increase and the effects of climate change are further worsening the situation and leading to increasing water scarcity in new areas. This is largely due to runoff, changes in precipitation patterns, and population increases. For example, in India, a 2013 model predicts that the percentage of people exposed to water

scarcity would increase from 70% in 2020 to 81% in 2050 if population change was the only factor (Gosling & Arnell, 2013).

Pollutants also affect water scarcity. Almost every river in Asia, Africa, and Latin America is affected by water pollution. Globally, 80% of industrial and municipal wastewater is released untreated due to the high cost of treatment, contributing to the contamination of otherwise freshwater (Boretti & Rosa, 2019).

Rainwater harvesting is a tool to counter water scarcity, especially in semi-arid or arid regions where rainy season is usually short. It involves altering or inducing runoff patterns to collect, store or use the runoff water. The types of water harvesting used vary widely depending on the terrain, climate, and needs of the region (Fikadu & Moldeamanuel, 2019; Oweis, Prinz & Hachum, 2001; Boers & Ben-Asher, 1982).

Study Area

Rajasthan is a state in northwestern India. It is largely a semi-arid desert with relatively little water. The current rate of decline of groundwater table is 1-3 meters per year, with over 80% of the state in critical condition for water exploitation (Kumar, 2020). This is a big issue, especially for the 70% of the state's population that is rural and engages in agriculture. Additionally, water scarcity generally impacts poorer communities disproportionately, making the situation for rural farmers even worse [DeNicola et al., 2015).

Since Rajasthan gets little rainfall and has no major lakes or rivers, people have to find other sources. The main water source in rural areas is groundwater in aquifers extracted through wells. This extraction leads to the depletion of groundwater, which, in turn, causes wells to dry up and farmers to dig the wells deeper. This cycle depletes the

groundwater levels rapidly, ultimately leading to the water table dropping to a level where it is not feasible to extract it through wells (KIGS, 2020).

The Kumarappa Institute of Gram Swaraj, or KIGS, is a non-profit–based in Rajasthan. In 2013, KIGS initiated efforts to increase the underground water table in several rural villages through rainwater harvesting for well recharge [KIGS, 2020; KIGS, n.d.). The focus of this study are the 118 well recharge structures constructed between 2018 and 2023 in 20 villages in the Chaksu block of the Jaipur district of Rajasthan (KIGS, 2020).

In the project villages in Chaksu, as with most villages in Rajasthan, agriculture is the primary source of income and livelihood. Water scarcity from droughts and uncertain rainfall affects the crop yield, often making farming unprofitable. Each farm has an open well that is 24 to 30 meters (80 to 100 feet) deep, but most of them are completely dry in the study area as the water table often stays lower than that–up to 46 meters (150 feet) deep. Many farmers in the study area grow crops that require as little water as possible, such as mustard and garbanzo beans, but they don't sell for as much in the market as crops such as wheat, which are more water-intensive (KIGS, 2020).

The study area's climate is semi-arid and the mean annual rainfall is 650 millimeters (mm). The area has often faced drought or significantly below-average rain for many decades. The terrain is primarily flat with less than 3% slope, and the soil is semi-loamy to loamy, meaning that it is not too sandy such that the water will seep into the ground, but is firm enough to allow water runoff.

For decades, the primary source of irrigation had been groundwater drawn from open wells. The region has hard rock aquifers underground, where groundwater is most

common and suitable for artificial recharge. The region's loamy soil allows for more control and redirection over water resources than rocky terrains, such as through rainwater harvesting, construction of subsurface barriers, and percolation tanks (KIGS, 2020).

Study Objectives and Research Questions

This paper seeks to assess the efficacy of KIGS's well recharge program through a mixed-method approach that includes quantitative data analysis and a qualitative assessment through semi-structured interviews with farmers. It measures water availability on three metrics that apply to each farm: the water level in the well, the amount of farmland irrigated with available water, and the number of hours the engine pumps water daily. These data were gathered for the year before the well recharge was implemented and every following year in December, a few months after the rainy season ends.

Specifically, this paper seeks to answer the following research questions:

a) Has the well recharge program led to increased water availability for agricultural use as measured by the following three metrics: water level in the well, the land area irrigated, and the amount of time the engine pumped water daily?

b) What is the farmers' qualitative assessment of the efficacy of the well recharge program?

Literature Review and Research Gap

Water harvesting techniques can be broadly categorized as micro-catchment systems and macro-catchment systems. In micro-catchment systems, surface runoff is collected

from a small catchment area. The rainwater flows to a location where it can be stored either in the soil profile to be consumed directly by the plants or in a storage area from where the water can be taken for later use. There are two main types of micro-catchment systems: on-farm systems and rooftop systems (Fikadu & Moldeamanuel, 2019; Oweis, Prinz & Hachum, 2001).

On-farm systems are simple, low-cost, and easily replicable (Fikadu & Moldeamanuel, 2019; Oweis, Prinz & Hachum, 2001; Boers & Ben-Asher, 1982). They allow soil erosion to be controlled and for sediments to be flowed along with the water and to the plants, helping them grow. Since the rainwater is collected on the farm site on which it will be used, it is usually not necessary to construct a elaborate water conveyance system. Furthermore, since the system is entirely on the farmer's land, the farmer has nearly total control over the specifics of the catchment and target. However, on-farm systems usually require continuous maintenance. Additionally, the water catchment system takes up land that could have been used for agriculture (Oweis, Prinz & Hachum, 2001).

Rooftop systems collect and store water from the roofs of buildings and other impervious surfaces (e.g., roads). The use of the water depends on the cleanliness of the surfaces it is harvested from and the users' needs, meaning that it is not limited to agricultural use. Usually, users do not store water from the first rain's runoff as it carries contaminants accumulated on the surface over a long time and thus may not be clean enough to use (Oweis, Prinz & Hachum, 2001).

In macro-catchment systems, runoff water is collected from a larger catchment area, benefiting a larger community. The larger scale of the system also comes with a higher construction cost. Catchments are usually outside of farm boundaries and travel

much further than micro-catchments (Fikadu & Moldeamanuel, 2019; Oweis, Prinz & Hachum, 2001; Boers & Ben-Asher, 1982). Due to the water catchment being outside of the farmers' land, they have little control over the system. Moreover, water rights are a major factor with macro-catchment systems, affecting the distribution of water to users between the catchment and destination areas (Oweis, Prinz & Hachum, 2001). Most macro-catchments have a runoff capture of 50% or less of the annual rainfall—much lower than micro-catchments. Water is usually stored in reservoirs, above ground or underground, but may sometimes be stored in the soil profile for use by plants or in underground aquifers for recharge (Oweis, Prinz & Hachum, 2001; Boers & Ben-Asher, 1982).

Overall, micro-catchment systems allow individual farmers to have more control over water collection and are much lower-cost and simpler to implement while still being effective. On the other hand, macro-catchment systems are better suited for large-scale water harvesting for bigger and distant communities.

Moreover, water traveling long distances on the surface faces contamination risks; and, in Rajasthan, evaporation losses due to the hot and dry climate. These drawbacks make macro-catchment less viable. With micro-catchment, on the other hand, catchment and storage areas are close together and on the farmers' land. Considering the advantages of storing the water quickly, the increased autonomy farmers get, the increased sediment flow to the plants, and its low cost and replicability, on-farm micro-catchment systems with underground water storage are better suited for the agricultural villages in rural Rajasthan.

Finally, while rainwater harvesting is used globally, there is little research on its efficacy for agricultural purposes. A couple of recent studies begin to fill this gap. Pari

et al. (2021) simulate the economic and environmental impacts of using ponds and flexible water storage systems while Yuan, Fengmin and Puhai (2003) estimates the impact of storing rain water on total crop yield in Gansu, China. Our research extends this line of inquiry by assessing the impacts of a real-world rainwater harvesting project on recharging aquifers through existing wells in a Global South region with a hot semi-arid climate with significant likelihood of water loss due to evaporation.

Materials and Methods

Case Study Well Recharge System

In the case study area, the well recharge system comprises a water collector that is constructed on one of the lowest points on the farmers' land. This concrete structure collects and naturally filters the rainwater that flows into it from the surrounding area. After getting filtered, the water goes into a plastic pipe that goes down the well, joining the water in the aquifer from which the farmers pump water (see Figure 1). Using the existing wells and underground aquifers for rainwater storage is convenient because it virtually eliminates the expense for constructing a storage system.

--Figure 1 Goes About Here--

The water catcher comprises three cells, each divided by walls with holes near the top. The water spills into the next cell only once it reaches the height of the holes, ensuring that anything denser than water is left behind because it sinks to the bottom of the cell. This process, repeated twice, is a cheap yet effective way to naturally filter the rainwater of unwanted objects, such as sand.

In the third cell, there is a plastic pipe that leads into the well to spill the water down and into the aquifer. There is also a removable valve between the third cell and

the pipe. This valve serves as a barrier to block excess water from going into the aquifer. This valve is opened during the rainy season so that the water flows into the pipe normally and exists solely as a safeguard.

Data Collection and Research Methodology

The study used a mixed-method approach to assess the effectiveness of the well recharge project, including quantitative data analysis and a qualitative assessment through interviews with farmers.

The water availability was measured on three metrics that apply to each farm: the water level in the well, the amount of farmland irrigated with available water, and the amount of time the engine could pump water daily. These data were gathered the year before the well recharge was implemented and for every following year in December, a few months after the annual rainy season ends.

All data used in the analysis are from the farms located in the Chaksu block where 118 well recharge structures were constructed between 2018 and 2023, of which 15 were constructed in 2018, 26 in 2019, 17 in 2020, 20 in 2021, 17 in 2022, and 23 in 2023.

Data are collected from each farmer annually. Data accuracy is a major issue with this data collection approach. Specifically, for the first two years after the well recharge system was implemented, farmers accurately observed and reported the data. However, after two years of water harvesting and significant increases in water availability, many farmers began to report data inaccurately. To maintain the study's integrity, the missing data were imputed from the previous year's data, but only when absolutely necessary. To reduce this data imputation, we used data only from three

years–the year before the construction of the recharge system (Year 0), the first year of recharge (Year 1), and the second year of recharge (Year 2)–for analysis. For example, for farms where water catchment started in 2018, data are included for 2017 to 2019; 2019-constructed systems have data for 2018 to 2020; and so on.

Next, we conducted the T-test of Dependent Samples to assess whether the averages of the data for all three metrics (the water level in the well, amount of farmland irrigated with available water, and amount of time the engine could pump water daily) are statistically significantly different before (Year 0) and immediately after implementing the well recharge program (Year 1), and for the first two years after the program implementation (Years 1 and 2).

In addition to the quantitative data collection and analysis, three individual farmers were interviewed, each who had well recharge implemented in various years and from different villages in the study area. Below are the questions asked to these farmers in July 2024 to gauge the impact they noticed from the project.

- How much land do you have, and how much of it did you use for agriculture before and after well recharge?
- Was your well dry before recharge?
- How long did your engine pump water per day before and after recharge?
- When you were first given the opportunity to implement well recharge, did you doubt about how well it would work and benefit you?
- Did you notice a difference in water quality before and after recharge?
- Did you start growing different types of crops after recharge?
- Do you believe the well recharge system would be greatly beneficial if it were implemented on a larger scale?

4. Results

4.1 Quantitative Analysis

As Figure 2 shows, the data show a consistent upward trend. Year 1 yields the most increase in all three metrics from before recharge (from 1.0 to 1.8 meters of water in the well, 1.5 to 2.0 hectares of irrigated area, and from 1.0 to 2.4 hours of engine run time). The water availability increased significantly in Year 2 as well—from 1.8 to 2.4 meters of water in the well, 2.0 to 2.4 hectares of irrigated area, and 2.4 to 3.2 hours of engine run time. The T-test of Dependent Samples between consecutive years' data show a statistically significance impact of well recharge at the p=0.05 level (see Table 1).

--Figure 2 Goes About Here—

--Table 1 Goes About Here--

4.2 Qualitative Analysis

Qualitative assessments back up the quantitative results through interviews with three farmers who had the well recharge system implemented on their land. Overall, the farmers' responses indicate that the well recharge had a significantly positive effect in many aspects, including ways the data could not measure.

Before recharge, the engines of Farmers A and b pumped water for just 1 hour per day. Now, they pump for 6. Even this number is a conservative estimate because many villages get electricity only for 6 hours per day.

With the significant increase in engine run time, Farmers A and B are able to irrigate more land. Farmer C's well recharge structure was constructed in 2023. Before recharge, the pump of Farmer C didn't draw any water, and he had to buy all of his water from neighboring farmers. Now he believes that after his first recharge from the 2024 rains, he will be able to irrigate 5 out of his 8 hectares of land with his own water.

Additionally, the increase in water gave farmers incentives to acquire more land. For example, Farmer 1 could irrigate only 2 hectares out of his 3-hectare farm, but after recharge, he purchased 1 more hectare and can irrigate all 4 hectares of land. All the farmers also switched to more water-intensive crops after recharge. Before recharge, Farmers A and B grew mustard, and Farmer C grew garbanzo beans. Now, all three grow wheat, which is more water-intensive but more profitable.

Furthermore, groundwater naturally carries minerals such as fluoride, but pure rainwater mixed with groundwater makes these minerals less concentrated, increasing the water quality. This is supported by the three farmers, who stated that the water quality increased after the implementation of well recharge, making their soil looser and more fertile. Farmer B said that his water had so much fluoride before recharging that it wasn't even suitable for bathing. But after recharge, the water became pure enough to be used for all domestic purposes.

When the farmers first heard about the well recharge system, all three were confident it would be effective. Farmer 1 believed that the activities of an NGO such as KIGS would be beneficial and thus trusted them to implement well recharge on their land. Farmer B reported that some people doubted the effectiveness of the well recharge program, but he was clear that it would work as he had already visited another farm where the well recharge program had been implemented and saw its benefits first-hand. Farmer C knew that if there is a well near a pond of collected rainwater, the pond water seeps into the well and down into the aquifer, increasing water availability. He figured that KIGS's project would work similarly since the rainwater will end up in the well, just without the intermediate pond.

Finally, all three farmers stated that if the well recharge project was implemented on a wider scale, then the project would provide the individual farmers more water and increase the ground water table region wide.

Discussion and Conclusion

Issue Recap

With rapid climate change and population growth, changes in weather and water runoff patterns are causing increasing water scarcity worldwide. The Indian state of Rajasthan is greatly affected because its primary water source, groundwater, is depleting, making most of the state vulnerable to water scarcity.

Agricultural villages feel the effect of this water scarcity acutely. The well recharge in the case study area through on-farm micro-catchment systems works to redirect rainwater into wells, increasing the water supply for the individual farmers and the whole region by collectively increasing the ground water table.

Interpretation of Results

This study assesses the efficacy of the well recharge program on three metrics: the water level in the well, the land area irrigated, and the time the engine pumped water in a day. The changes in the data over the years show a statistically significant increase in water availability. A qualitative assessment of the program through interviews with three farmers shows significant increases in water availability and quality. The increases allow farmers to pump more water, purchase and cultivate more land, grow more valuable water-intensive crops, and use better quality water that improves their soil fertility and is safer for domestic use.

The quantitative findings are even more notable because conservative metrics were used to estimate water availability. Specifically, the area of land irrigated is a conservative estimate of water availability because water availability is not the only factor that affects it. If the farmer can already irrigate all of their land, they will report the same value of irrigated land every following year even if water availability increases because they cannot irrigate more land than they have, thereby not accurately representing the change in water availability. Additionally, if a farmer switches to a more water intensive crop and thus is not able to irrigate additional land, it will appear as if water availability is lower than it actually is.

Furthermore, the duration that the farmers' engines pump water is also a conservative estimate of water availability because a farmer can change the pressure with which the water comes out of the nozzle, thus changing the engine run time. Because farmers tend to increase water pressure when more water is available, it may indicate a slower growth of water availability than what is true. In addition, as previously mentioned in the section titled "Qualitative Analysis," many villages get electricity for less hours than many farmers may potentially be able to pump water, further lowering estimates of this metric.

Finally, even though this study does not control for other time-variant factors, such as rainfall fluctuations, that could have impacted the ability of the aquifers to recharge, our time-series data address this issue to some extent; for example, by finding that for every year during the study period, the water levels in wells before recharge were always less than after recharge irrespective of the year the well recharge program was implemented.

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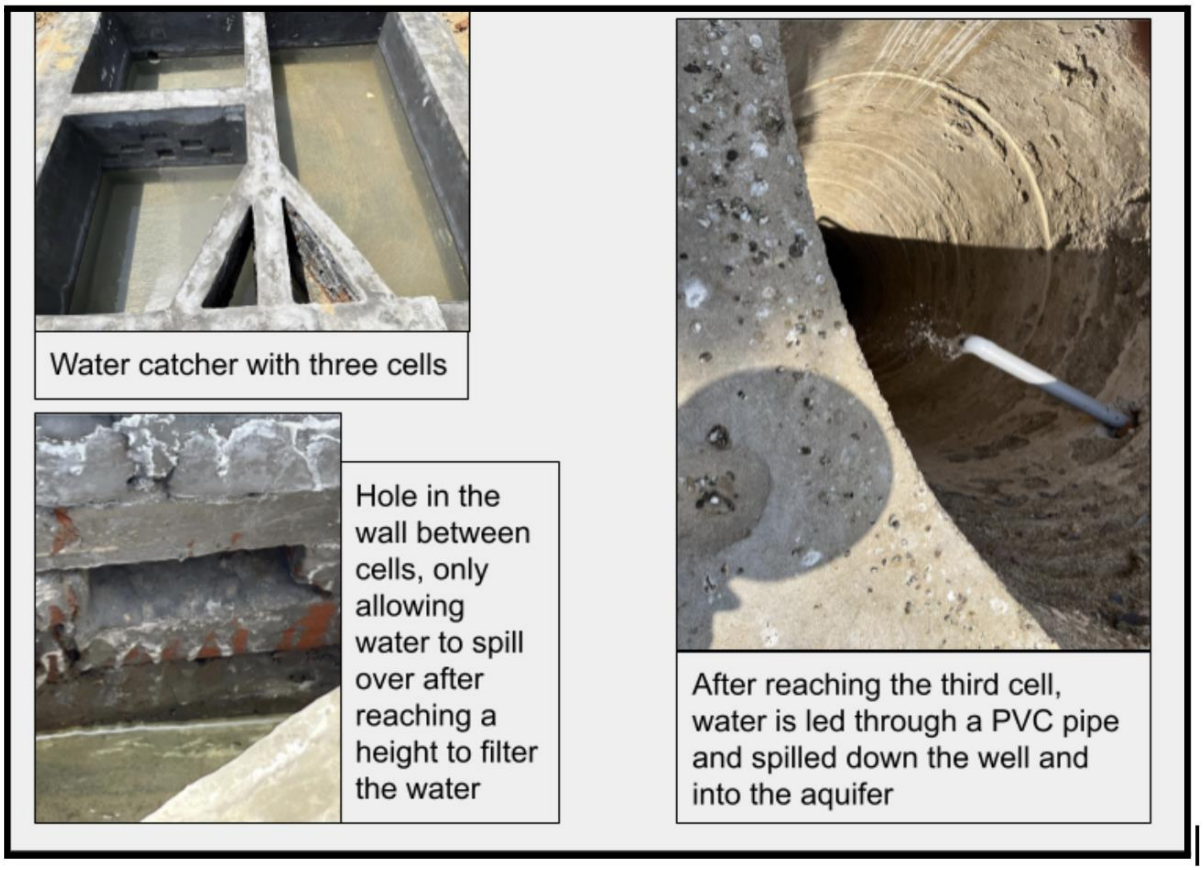
Table 1. Results of T-test of Dependent Samples

Metrics	Averages before recharge (Year 0) and in year 1 (p-values in parenthesis)	Averages in Years 1 and 2 (p-values in parenthesis)
Water level (in meters)	1.0 and 1.8 ($1.31 * 10^{-12}$)	1.8 and 2.4 ($6.54 * 10^{-7}$)
Irrigated area (in hectares)	1.5 and 2.02 ($2.64 * 10^{-11}$)	2.0 and 2.4 ($9.79 * 10^{-11}$)
Engine running time (in hours)	1.0 and 2.4 ($1.73 * 10^{-14}$)	2.4 to 3.2 ($3.47 * 10^{-7}$)

Figure 1. Water recharge structure



Source: Authors

Figure 2. Data trend for the three metrics