Conservation and harvesting of rainwater for sustainable agriculture in Kachho, Sindh, Pakistan

Naveed Noor[1], Zhang Wanchang[2], Noor Hussain Chandio[1], Gohar Ali Mahar[3], Ghani Rahman[4]

[1] Department of Geography, Shah Abdul Latif University, Khairpur, Pakistan
[2] Aerospace Information Research Institute (AIR), Chinese Academy of Sciences (CAS), Beijing, China
[3] Department of Geography, Federal Urdu University, Karachi, Pakistan
[4] Department of Geography, University of Gujrat, Punjab, Pakistan
* Corresponding: hussain.chandio@salu.edu.pk

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Abstract. Rainwater irrigation is relatively an uncommon practice in Pakistan, yet certain areas still utilize rainwater harvesting to address water scarcity. A north-south oriented belt, parallel to the Khirthar foothills and along the Indus River floodplain in Sindh province, has been identified as suitable for rainwater-based agriculture. Over time, easterly alluvial deposits have expanded, supporting agricultural growth. The main objective of this study was to explore the potential of rainwater harvesting and storage in Kacho, Sindh, for sustaining agriculture and mitigating water shortages. To achieve this, field surveys, water quantification techniques, construction of small reservoirs, and satellite image analysis were applied to assess available water resources and cultivation potential. Research findings indicate progressive improvements in water conservation, with 33.3% retained in 2017, 44.4% in 2018–2019, 38.9% in 2020, 66.6% in 2021, 88.5% in 2022, and 107.5% in 2023. Correspondingly, wheat productivity has increased from 450 kg in 2017 to 815 kg in 2023 in the selected study area. These findings demonstrate the effectiveness of rainwater irrigation in mitigating water shortages and enhancing crop yields. Ultimately, sustainable rainwater conservation is a viable solution for strengthening food security and agricultural resilience in arid regions of Pakistan.

Keywords: Khirthar Mountain, rainwater harvesting, rainwater rivulets, agriculture patterns, alluvial deposits.

1. Introduction

Water is an essential component of the broader ecosystem, fundamental to all life, biodiversity and ecological balance (Sargen, 2019). However, freshwater scarcity has become a global challenge, affecting not only arid regions but also areas with relatively abundant resources. Several factors contribute to this growing problem, including low storage capacity, poor infiltration rates, erratic precipitation patterns influenced by monsoons and high evapotranspiration demand (Anwar & Chandio, 2012). Understanding these dynamics is essential for developing effective water management strategies and ensuring sustainable resource availability.

Mountains cover more than one-fifth of the Earth's surface and are home to 12% of the global population, with half residing in the Asian region. While some regions of Pakistan remain submerged under floodwaters, others are experiencing severe drying due to the adverse impacts of climate change. Pakistan is among the top countries facing a serious threat of water scarcity in the world, where situation has intensified due to climate change. Agriculture, which remains the backbone of the national economy, faces severe constraints from both droughts and floods (Miandad et al., 2025). Approximately 80% of Pakistan's land area falls within arid or semi-arid zones, with the majority of the population dependent on surface and groundwater resources of the Indus Basin (Ahmad, 1994). The country's water storage capacity is extremely limited to only 30 days, compared to recommended minimum of 1,000 days (Davies, et al., 2016). Climate projections suggest further reductions in the Indus River flows due to declining snow and glacier melt, placing food and water security at high risk (Khames et al., 2022). Recent studies confirm this downward trend in river inflows (Savitsky, et al., 2013), although more recent evidence highlights the accelerating pressures from population growth and climate extremes (Dawood et al., 2018; Rahman et al., 2022).

Sindh province, which lies in the lower Indus Basin, clearly illustrates these challenges. The province is marked by a dual problem: while recurrent flooding devastates many areas, regions such as Kachho remain chronically water-scarce. Located between the Indus floodplain and the Khirthar Mountains, Kachho is entirely dependent on rainfall and hill torrents for cultivation (Chandio et al., 2019). Droughts frequently disrupt agricultural production, forcing temporary migration, while limited groundwater availability at depths of 250–450 feet makes pumping prohibitively difficult.At the same time, seasonal hill torrents from the Khirthar catchments flow toward Manchar Lake and the Indus River, with much of this water left unutilized on the upper terraces. This paradox of surplus floodwater and acute drought reflects the urgent need for innovative water management in Sindh.Rainwater conservation has emerged as one of the most viable strategies to address these challenges, particularly in drought-prone and dryland regions. Historically, rainwater harvesting has played a pivotal role in sustaining civilizations. Archaeological evidence shows that the Indus Civilization, the Roman Empire, and ancient South Asian societies constructed reservoirs, wells, and ponds to capture rainwater for irrigation and drinking (Oweis et al., 2004; Kamash, 2013; Meter et al., 2014). Such practices were not confined to antiquity—modern research has shown that rainwater harvesting is among the most cost-effective and sustainable approaches to improving water security in arid regions (Bhinde & Shukla, 2019; Rastogi et al., 2024). In the context of Pakistan, where rainfall is highly seasonal and concentrated within a short monsoon window, the storage and systematic use of rainwater can play a transformative role in strengthening agricultural resilience.

Despite its potential, rainwater harvesting in Sindh has received limited attention, particularly in dryland areas such as Kachho. While the Indus Basin irrigation system dominates agricultural water supply, the western tributaries of the Khirthar Mountains remain largely unexploited for cultivation. Yet these tributaries form fertile alluvial fans and deposits at the foothills, offering significant potential for crop production. Local farmers have demonstrated the feasibility of small-scale rainwater irrigation since 2017, progressively expanding cultivated land each year. These community-led initiatives highlight the opportunities for scaling up through systematic conservation and storage measures.

In this context, the present study aims to assess the potential of rainwater harvesting and storage in the western catchments of the Khirthar Range to support sustainable agriculture in Kachho, Sindh. By integrating field observations, water quantification, reservoir construction, and satellite image analysis, the research evaluates both the availability of rainwater resources and the agricultural outcomes of their use. The study contributes to ongoing debates on climate adaptation and water management by demonstrating how localized rainwater conservation can mitigate scarcity, improve crop yields, and promote socioeconomic resilience in one of Pakistan's most vulnerable regions.

2. Study area

This study was conducted in the Kacho region, situated between the Flood Protective Bank (FPB) and the Khirthar Mountains, spanning the Kamber-Shahdadkot and Dadu districts of Sindh province (Fig. 1). The region lies on the windward side of the Khirthar Range and covers approximately 370,321 acres. Locally recognized as a drought-prone zone, Kachho is highly vulnerable to climatic extremes, where recurrent droughts often force temporary migration of local communities (Chandio et al., 2019). Kachho's climate is classified as semi-arid, with an average annual rainfall of only 5.1 inches, distributed erratically across seasons. The groundwater table lies at depths of 250–450 feet, making extraction costly and unsustainable.

Agriculture and livestock form the backbone of the local economy, but farming depends almost entirely on seasonal hill torrents (Nai) originating from the Khirthar Mountains. These torrents frequently bring destructive flash floods during the monsoon, damaging crops and settlements (Shakir, 2022). Topographically, the region is characterized by upper terraces, alluvial fans, and fertile floodplains formed through long-term weathering and deposition processes. The Khirthar Range itself contains nearly fifty perennial and non-perennial springs, some large enough to irrigate up to 500 acres of land. Despite the frequent occurrence of floods, much of the rainwater remains unutilized, as effective storage structures are limited. The soils of Kachho are fertile, comprising silty and clayey deposits suitable for cultivating wheat, rice, sorghum, millet, and seasonal vegetables (Khan et al., 2011; Bhatti et al., 2009). Historically, farmers have relied on natural diversions of hill torrents to irrigate seasonal crops. In recent years, small reservoirs and community-based water diversions have been developed to improve water availability and reduce flood damage (Singh & Basu, 2022). These efforts demonstrate the potential for expanding rainwater harvesting in the area, which remains the central focus of this study.

3. Materials and Methods

The primary aim of this study is to explore and assess the potential storage and harvesting of rainwater flowing from the upper western side toward the catchment area of the Khirthar Range. Traditional methods of water quantification have been applied to measure and calculate available water resources. Additionally, the study seeks to irrigate unused upper terraces of alluvial deposits and identify new land parallel to the mountain, where alluvial deposits and alluvial fans are present.

3.1. Data Collection

3.1.1. Field visits

A systematic reconnaissance of the upper area and each rivulet was conducted, where depth and storage capacity were observed. The entire region, including alluvial fans and deposits scattered across the hilly terrain, was examined. This assessment provided a broader perspective, revealing that the potential cultivation area is significantly larger than initially estimated. Discussions with local farmers, landowners, and community members highlighted the importance of water storage and proper drainage in expanding cultivated land. By implementing effective irrigation strategies, rainwater could be safely directed to the mainstream, ensuring sustainable agricultural development in the region.

3.1.2. Hydrological Data

Numerous rivulets from the Balochistan Plateaus flow into Sindh via the Khirthar Mountain, ultimately draining into local lakes such as Manchar, Hamal, Chagro, and Saroh (Fig. 1). Eventually, the rainwater crosses the research area and reaches the Arabian Sea via the Indus River. Among these, eight Non-Perennial Rain Water Rivulets (NPRWR) are particularly well-known, as they significantly contribute to filling the aforementioned lakes. The maximum recorded water flow of these eight rivulets is 809,168 cusecs during peak rainy seasons, while the minimum flow is 212 cusecs in dry months (Chandio, et al., 2023). Across the Khirthar Range, rivulets transport over 500,000 cusecs of rainwater into various lakes within the Kamber-Shahdadkot and Dadu Districts during the monsoon season. Traditional methods have been used to measure water flow quantity from each rivulet, with depth recorded in feet. Farmers utilize this water based on its available depth, which also determines the calculated quantity. A small water reservoir was constructed over the Mazarani Rivulet (Mazarani Nai) to enhance water storage. The maximum flow of the Nai is 85,000 cusecs, while the minimum recorded flow in dry months is 29 cusecs (Fig. 2). The reservoir measures 1,315.73 feet in length, 60.6 feet in width, and 15 feet in depth, covering a total area of 1.26 square kilometers (Government of Sindh, 2020). Its

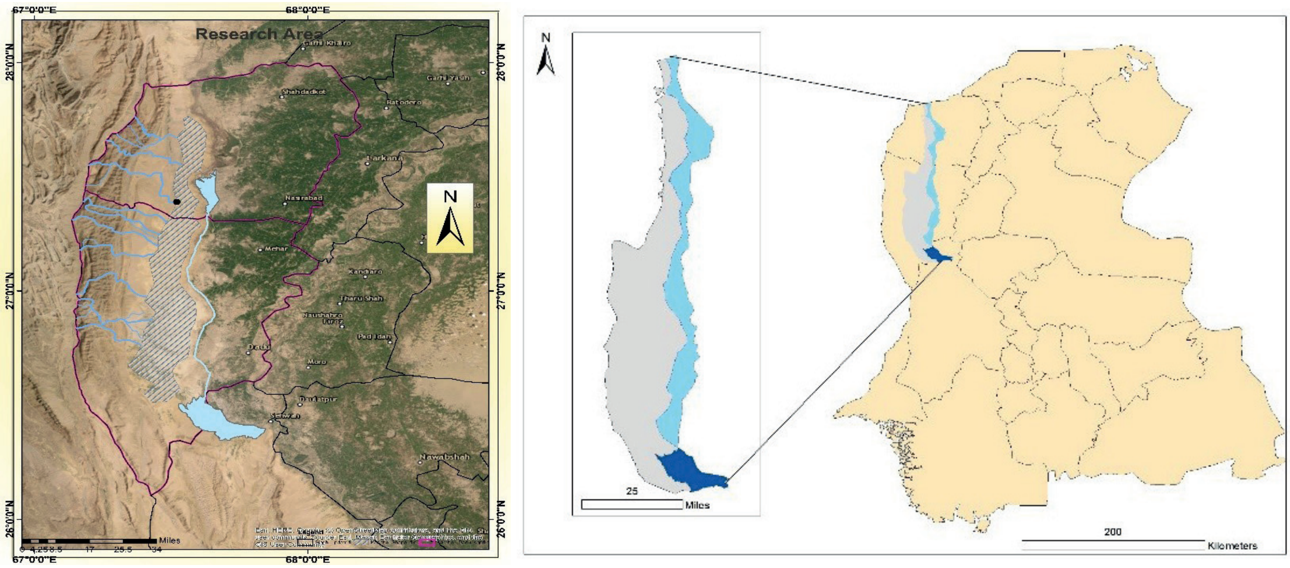

Figure 1. Location map of the study area

water storage capacity is 5,760.72 cubic meters (203,437.9 cubic feet). During dry months, only 45 cusecs of water are released from the reservoir to support sustainable irrigation. The geographical location of the reservoir was strategically selected based on the natural slope of the area to optimize water retention and distribution.

3.1.3. Satellite Image Study

This study was further evaluated using satellite data, specifically Landsat images from the post-monsoon period of 2023, downloaded via Earth Explorer. The images were ortho-rectified and geometrically corrected, ensuring spatial accuracy. They were projected onto the Universal Transverse Mercator (UTM) coordinate system, using the WGS-84 datum for consistency. To enhance visualization, the image of the study area was processed into a false-color composite and cropped to focus on specific regions of interest. Spectral analysis was conducted based on band variations, with a 6-5-4 band combination applied to highlight natural features (Fig. 2). In this processed image, the floodplain of the Indus River is clearly visible, along with parallel water flow from the catchment to Manchar Lake. Additionally, terraces of alluvial deposits at the foothills of the Khirthar Range are distinctly enhanced, providing valuable insights into the region's hydrological and geological characteristics.

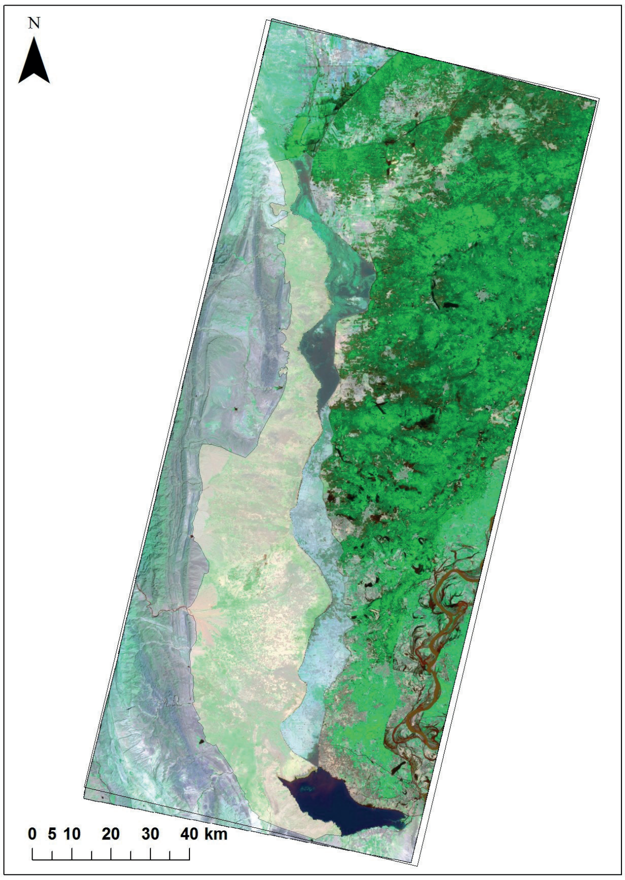

Figure 2. Satellite view from the Landsat image dated 2023

3.2. Data Analysis

3.2.1. Water Requirement Calculation (WRC)

The formula used for water requirement calculation is:
WRC = (Available water (in cusces) x required irrigating water)/cultivated land (acres).

3.2.2. Conversion of Flow Units

Cusec (cubic feet per second) represents the rate of water flow, it is often necessary to calculate the total volume of water delivered over a specific time period, typically a day. To achieve this, the cusec value is multiplied by 86,400—the total number of seconds in a day—yielding the overall water flow volume in cubic feet per day.

To convert the total volume of water from cubic feet per day to acre-feet per day, we must determine how many cubic feet are required to irrigate an acre-foot. Since one acre-foot is equivalent to 43,560 cubic feet—based on the standard acre measurement of 43,560 square feet—we divide the total water volume (in cubic feet per day) by this value to obtain the corresponding amount in acre-feet per day.

Total volume (acre-ft/day) = Total volume (ft^3/day) / Volume per acre-foot (ft^3/acre-ft)

Example:

A reservoir delivers water to agricultural land at a rate of 1 cusec. We want to find out how many acre-feet of water the farm receives in a day.

- Total Daily Flow: 1 cusec * 86,400 seconds/day = 86,400 cubic feet/day
- Conversion to Acre-Feet: 86,400 cubic feet/day / 43,560 cubic feet/acre-foot ≈ 1.98 acre-feet/day (Khalioq, 2006).

So, the canal provides water to agricultural land with approximately 1.98 acre-feet of water per day at a flow rate of 1 cusec (Asawa, 2006).

Therefore, Available water x 1.98-acre land

404,963 x 1.98 = 801,826 acres of land per day, this is except for rainfall and other natural precipitation.

3.2.3. Reservoir Capacity Estimation

The constructed reservoir on the Mazarani Nai was measured for its length, width, and depth, and its storage capacity was calculated. During dry months, controlled releases of 45 cusecs of water were applied to support irrigation.

3.2.4. Satellite Image Analysis

The Landsat imagery was analyzed to highlight geomorphological and hydrological characteristics of the study area. Features such as alluvial deposits, terraces, and the floodplain belt were identified, and spectral band combinations were used to assess agricultural and hydrological potential.

4. Results

The results of various approaches indicate that rainwater from the hill torrents of the Khirthar Mountain is sufficient to cultivate the barren land in the study area, provided that rainwater from just eight rivulets is effectively conserved. Under current conditions, only a small portion of land is cultivated, while a significant surplus of water remains available for future cropping seasons. These findings highlight the excellent agricultural potential of the land, with a capacity far greater than currently utilized. Additionally, water resources for lakes such as Manchar remain sufficient to support a sustainable ecosystem and environment, reinforcing the viability of long-term water conservation strategies.

Satellite data confirms that the western side of the Indus floodplain, located at the foothills of the Khirthar Range, exhibits a diverse range of natural features and ecosystems. From the upper catchment area, 8 entrances have been identified, each serving as a rivulet (Table 1). These rivulets contribute to the formation of fertile alluvial fans, which hold significant potential for rangeland development or agricultural cultivation. Additionally, at the foothills, a large, continuous belt of silt deposits is prominently visible. This fertile land has formed over time due to the consistent flow of rainwater from the western Khirthar catchment area. Satellite imagery also reveals lush vegetation toward the eastern portion, indicating the long-standing influence of the Indus River floodplain, which has sustained irrigation in this region for centuries.

Figure 2. Oblique view of the reservoir

Data collected directly from farmers and landowners (Table 1 and Table 2) indicates that cultivation began in

Table 1. Non-perennial (Nai)River with location and flow

S.#	Names of Rivulets	Geographical location	Quantity (Cusecs)		Average
			Maximum (Monsoon season)	Minimum (Dry months)	
1	Mazarani Nai	27.22.33.62 67.30.35.17	85,000*	29	42,514.5
2	Sagra Nai	27.18.24.07 67.23.20.78	72,000*	26	36,013
3	Buri Nai	27.14.31.53 67.19.33.18	32,000*	37	16,018.5
4	Makhi Nai	27.22.53.07 67.19.7.00	41,000*	35	20,517.5
5	Gaj Nai	26.52.40.96 67.18.43.17	295,168**	50	147,609
6	Sita Nai	27.32.19.72 67.34.4.45	76,000*	41	38,020.5
7	Khenji Nai	27.40.23.56 67.26.48.69	43,000*	27	21,513.5
8	Salary Nai	27.8.29.44 67.17.9.94	165,000*	47	82,523.5
	A total water volume of eight rivulets		***809,168***	***212***	***404,690***

Source: Lal et al., 2011** & newspapers, personal visits and interviews*

Table 2. Area under cultivation and production per acre

S. #	Year	Released water (cusec)	Irrigation (number of turns)	Area under cultivation (Acres)	Production per acre (kg)	increase in production (kg)	Increased in production per acre %
1	2017	45	4	60	450	----------	---------
2	2018	45	3	60	475	25	5.5
3	2019	45	3	60	550	100	22.2
4	2020	45	4	70	600	150	33.3
5	2021	45	3	90	760	310	68.8
6	2022	45	3	120	810	360	80
7	2023	45	3	145	815	365	81.1

2017 with 60 acres of land. In the first cropping year, wheat production averaged 450 kg per acre, increasing to 475 kg in 2018 and 550 kg in 2019. By 2020, production reached 600 kg per acre, requiring four irrigation cycles. In 2021, production rose to 760 kg per acre, with the soil requiring three irrigation cycles. The trend continued in 2022, with production reaching 810 kg per acre, and in 2023, production peaked at 815 kg per acre, maintaining the three irrigation cycles (Table 2).

5. Discussion

Agriculture remains both a profession and a passion in rural areas, with local growers have to adopt alternative livelihoods. Rainwater conservation plays a crucial role in enhancing the social and economic value of the research area. Many residents who migrated due to the 2022 floods have now returned to re-cultivate their agricultural land. However, water scarcity continues to pose a significant challenge, potentially reducing crop productivity. In regions like the study area, where water shortages are persistent, farmers may need to rely on rainwater harvesting as a primary irrigation method. The construction of small water reservoirs is essential for increasing water availability and ensuring a stable agricultural water supply. These reservoirs not only support irrigation but also recharge groundwater levels and maintain water quality. Despite its fertile potential, the study area remains barren due to water shortages. The rainwater rivulets (hill torrents) of the Khirthar Mountain have historically caused property damage and human loss. Effective management of these rivulets—through government and NGO-led initiatives—could facilitate water storage and irrigation, reducing food security concerns in the region. To optimize agricultural productivity, it is recommended to adopt modern irrigation techniques such as drip irrigation systems, introduce drought-tolerant crops, and implement advanced water management practices. The area holds significant potential for constructing additional small reservoirs, which could further expand irrigated land.

Over the past 30 years, the study area has experienced both droughts and floods. Between 1995 and 2001, a prolonged drought affected the region, followed by intermittent heavy rainfall. In 2009 and 2010, flooding conditions emerged, and

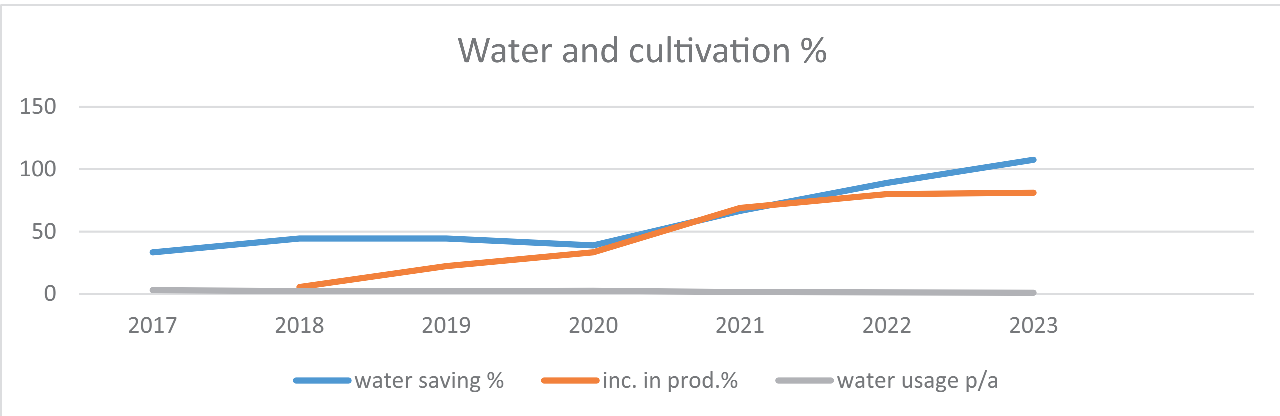

Figure 3. Water saving, water usage, and cultivation during the research period

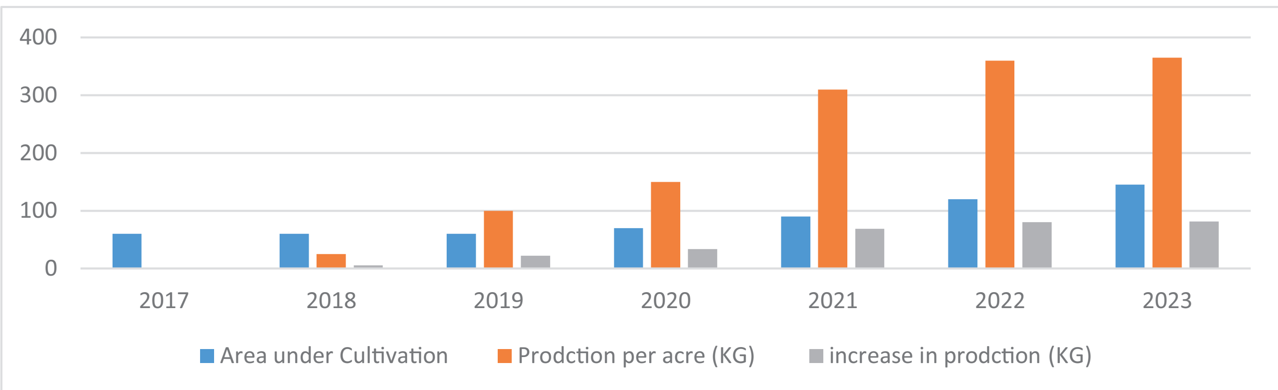

Figure 4. Area under cultivation and increase of production

in 2022, three consecutive days of heavy rainfall led to severe flooding, impacting Dadu, Kamber-Shahdadkot, and other western and northern districts of Sindh.

This research, conducted from 2017 to 2023, aimed to promote sustainable agriculture and address socioeconomic challenges in the study area. Initially, in 2017, wheat crops were cultivated on 60 acres, with an average yield of 450 kg per acre. Production increased to 475 kg in 2018, 550 kg in 2019, and 600 kg in 2020, with 45 cusecs of rainwater available for irrigation. By 2021, cultivation expanded to 90 acres, yielding 760 kg per acre, followed by 120 acres in 2022 and 145 acres in 2023, maintaining three irrigation cycles annually. Harvesting was completed between late March and early April.

Findings suggest that water from western tributaries should be properly managed to ensure long-term sustainability. Constructing additional water storage facilities, similar to Manchar Lake, would allow floodwater to be stored and utilized during drought years. Furthermore, rainwater conservation will play a critical role in fostering sustainable agriculture and supporting socioeconomic development in the region. Despite the region's agricultural potential, water scarcity remains a persistent barrier to productivity. While the Sindh Irrigation and Drainage Authority (SIDA) and the National Water Policy (2018) have aimed to improve water governance and promote sustainable irrigation but their implementation in this region has been limited. Some NGOs have also supported community-based water conservation projects that include small-scale reservoir construction and rainwater harvesting awareness campaigns. However, a lack of coordination between government agencies and local and internation NGOs, insufficient funding and limited technical capacity continue to hinder long-term water management. Bridging these gaps through integrated policy frameworks and localized interventions is essential to ensure water security and agricultural resilience.

This study acknowledges several limitations that may influence the results of its findings. The analysis relies on farmer-reported data, which may be subject to biasness or reporting inaccuracies, particularly regarding crop yields and irrigation volumes. The study period spans over a very small period of time, which, while informative bu may not fully capture long-term cumulative impact of water management interventions. Additionally, the absence of continuous hydrological monitoring may have constrained the precision of hydrological analysis. Future research should incorporate longer timeframes, automated data collection tools and broader stakeholder engagement to strengthen the reliability and applicability of results.

6. Conclusion

Water scarcity and natural disasters, such as droughts and flash floods, are common in Pakistan. A barren alluvial belt is found on the eastern side of the Khirthar Range, between Sindh and Balochistan Provinces. In recent years, farmers have initiated cultivation in this region, expanding from 60 acres in 2017 to 145 acres in 2023. This study identifies the current cultivation as a test case, suggesting that larger tracts of land could be irrigated using westerly flowing rivers in the future. Research findings indicate that the fertile land in the area is significantly larger than initially estimated, with ample water resources available to irrigate uncultivated land. Although the region is considered remote, the construction of water reservoirs would enable crop cultivation and raise the groundwater table. Satellite imagery has provided promising insights, reinforcing the potential for agricultural expansion. Effective water management and harvesting could facilitate the rapid cultivation of thousands of acres in a short period. Ultimately, rainwater conservation is a key solution to addressing water scarcity, which exacerbates challenges such as food insecurity, economic instability, poverty, and unemployment. Sustainable rainwater harvesting will support agricultural development, strengthen economic growth, and enhance social stability. Through effective management and conservation practices, research suggests that groundwater levels, water quality, crop yields, and green cover will improve, fostering long-term agricultural sustainability in the study area.

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