UDK-528.48

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THE ROLE AND IMPORTANCE OF RAINWATER HARVESTING (RWH) TECHNOLOGIES IN IMPROVING WATER SUPPLY IN IRRIGATED LANDS

ANNOTATION

Annotation. *Rainwater Harvesting (RWH) is considered an important strategy for enhancing agricultural sustainability and ensuring water security in arid regions. Particularly under conditions of limited water resources and increasing impacts of climate change, RWH technologies play a significant role as an alternative water source. This approach not only reduces water scarcity but also contributes to stabilizing crop yields, maintaining soil moisture, and improving the resilience of agroecosystems.*

This article provides a comprehensive analysis of the effectiveness of RWH technologies, focusing on investment directions, evaluation methodologies, and Earth Observation (EO) technologies. The study examines the economic, environmental, and social impacts of RWH systems based on existing scientific literature, project reports, and statistical data. In particular, the efficiency of investment projects, their long-term sustainability, and their impact on agriculture are evaluated.

From this perspective, the use of Earth Observation (EO) technologies significantly enhances the processes of monitoring and evaluating RWH systems. EO data enable continuous observation of indicators such as land cover changes, soil moisture, and vegetation indices, thereby supporting more scientifically *grounded decision-making processes. Furthermore, the integration of EO and GIS technologies serves as an important tool for improving the efficiency of RWH projects, ensuring rational use of resources, and promoting sustainable development.*

Keywords: *rainwater harvesting, GIS, geospatial analysis, irrigated lands, Rainwater Harvesting (RWH), Zai method, Samarkand*

INTRODUCTION

At present, in the agricultural sector of our country, large-scale irrigation and land reclamation measures are being implemented within the framework of state programs aimed at improving water use efficiency, enhancing the ameliorative condition, and strengthening water supply in irrigated lands. At the same time, global climate change, population growth, expansion of economic sectors, and the development of new lands in neighboring regions are contributing to a steady increase in water demand and the growing scarcity of water resources [1].

Under conditions of water scarcity in irrigated areas, Rainwater Harvesting (RWH) technologies are increasingly considered an important climate adaptation strategy. Particularly in semi-arid regions such as the Samarkand region, this approach expands opportunities for efficient water use.

By collecting and storing rainwater, soil moisture can be increased, which in turn extends the growing period of crops and stabilizes yields. At the same time, these technologies play a significant role in reducing soil erosion, limiting surface runoff, and improving agroecological conditions.

In recent years, various projects on water resource management have been implemented in Uzbekistan; however, rainwater harvesting systems have not yet been widely adopted. This issue is especially critical in regions experiencing high levels of water scarcity.

Practice shows that several factors hinder the widespread implementation of these technologies, including:

- insufficient financial resources

- limited technological knowledge and skills
- weak institutional support

In addition, the lack of reliable statistical data on existing projects and the absence of systematic monitoring of their effectiveness hinder the large-scale implementation of previously developed practices.

Therefore, analyzing rainwater harvesting systems while considering regional characteristics, identifying how and where resources are allocated, and evaluating the conditions under which these systems are most effective are of significant scientific and practical importance.

Determining priority areas for the implementation of rainwater harvesting technologies, ensuring rational allocation of resources, and analyzing lessons learned from previous projects are essential. In particular, under the conditions of the Samarkand region, this approach serves as a key factor in improving the efficiency of water resource utilization.

LITERATURE REVIEW

Rainwater Harvesting (RWH) technologies have been widely studied by numerous researchers as an effective tool for improving water resource utilization in arid and semi-arid regions. In particular, scholars such as Wouter H. van der Zaag and Klaus Hubacek emphasize the importance of using alternative water sources in water resource management. Studies on the impact of RWH technologies on agriculture, conducted by Theib Oweis and Ahmed Hachum, demonstrate that water harvesting techniques are effective in increasing crop productivity in semi-arid regions. According to their findings, micro-catchment methods and infiltration technologies significantly enhance yields under drought conditions by maintaining soil moisture.

Furthermore, research by William Critchley and John Siegert highlights that RWH systems not only improve agronomic efficiency but also enhance the economic stability of farming systems. At the same time, they stress the importance of considering local conditions when implementing RWH technologies. In terms of socio-economic impacts, studies by Michael M. Ghimire and Yuting Zhang underline the importance of long-term evaluation. According to them, short-term results do not fully reflect the actual effectiveness of RWH systems, making long-term monitoring essential.

In recent years, the use of modern technologies—particularly Earth Observation (EO) and Geographic Information Systems (GIS)—in evaluating RWH systems has been expanding. Research conducted by Chris Reij demonstrates that EO technologies enable the monitoring of land cover and vegetation changes, thereby providing opportunities to assess the effectiveness of RWH projects over large areas[11].

At the same time, studies by Nathaniel BenYishay and Niraj Singh emphasize the need to apply causal inference approaches when evaluating the effectiveness of investment projects. They argue that many projects suffer from methodological limitations, which hinder accurate assessment of outcomes.

Overall, the literature review indicates that RWH technologies have significant potential to ensure agricultural sustainability. However, their effective implementation requires scientifically grounded approaches, modern monitoring technologies, and comprehensive evaluation methodologies.

The economic efficiency of RWH technologies remains a significant constraint for their adoption and long-term sustainability (Table 1). Certain RWH methods, such as macro water harvesting systems, require several years to recover initial construction costs, making them less attractive for smallholder farmers seeking quick returns. These systems demand substantial financial, material, and technical resources; however, their long-term benefits often justify the investments. In contrast, micro water harvesting systems involve lower initial costs, provide moderate short-term benefits, and may be more suitable under certain conditions.

Limited market opportunities often prevent increased agricultural productivity from translating into higher income. Weak market linkages, along with insufficient collaboration between research, extension services, and commercial sectors, further restrict farmers' ability to benefit from productivity gains.

In addition, the impact evaluation of RWH systems is often limited, making it difficult to establish direct causal relationships between interventions and socio-economic outcomes. In this regard, modern Earth Observation technologies—remote sensing and GIS—serve as important tools. These technologies provide cost-effective and comprehensive solutions for monitoring regional conditions and are particularly useful in data-scarce or complex environments.

Practical experience shows that many projects have failed to achieve expected results. The main reasons include:

- lack of institutional support for smallholder farmers
- high maintenance costs of systems
- limited access to market infrastructure

Moreover, insufficient involvement of local communities in the planning and implementation stages reduces project sustainability. Conversely, active community participation strengthens ownership and facilitates the scaling-up of successful practices.

Additionally, systemic challenges—such as weak governance, lack of policy incentives, and insufficient enabling conditions—limit farmers' ability to adapt to climate change. Many investment projects have failed to adequately consider critical factors such as land tenure, erosion risks, and drought impacts, negatively affecting their long-term sustainability[8].

Modern approaches in agriculture indicate a transition from models focused solely on smallholder farmers toward more diversified production systems. In this context, it is essential to integrate rainwater harvesting systems with national policies and economic development strategies.

DISCUSSION

One of the most critical challenges today is the lack of clear and systematic data on investments. The absence of comprehensive information on project budgets, implementation timelines, outcomes, and lessons learned significantly hinders the effective planning of future initiatives. Although substantial financial resources are being allocated globally toward climate adaptation and sustainability, the transparency and accessibility of data related to these investments remain insufficient.

For the effective development of rainwater harvesting (RWH) systems in the future, it is essential to:

- conduct a thorough analysis of previous project experiences
- develop approaches adapted to regional conditions
- introduce modern technologies
- improve management systems

The analysis of existing scientific studies indicates that most research is either narrowly focused or methodologically limited. Many studies concentrate primarily on farm-level outcomes while failing to adequately account for regional and systemic factors.

In general, research can be classified into two main categories:

1. **Experimental studies** – which assess the impact of RWH technologies on crop productivity
2. **Observational studies** – which examine relationships with socio-economic outcomes

For instance, micro water harvesting technologies (such as terraces and the Zai method) can significantly increase crop yields. Large-scale water harvesting systems (such as ponds and small dams) enhance soil moisture and demonstrate high effectiveness, especially when combined with fertilization practices.

However, experimental studies often overlook broader social and environmental factors, while observational studies frequently fail to establish clear causal relationships. Therefore, a comprehensive and multidisciplinary approach is required.

Currently, the reduction of water resources and the impacts of climate change are negatively affecting the productivity of irrigated lands. In Uzbekistan, agriculture largely depends on artificial irrigation systems.

The use of rainwater harvesting:

- reduces water scarcity
- increases crop productivity
- ensures ecological sustainability

Therefore, the main objective of this study is to identify suitable areas for rainwater harvesting and to develop an appropriate model.

The experience gained from RWH projects and investments demonstrates that these technologies are an effective tool for water resource management in arid regions. Their application in Uzbekistan is particularly relevant, as a significant portion of the country lies within arid and semi-arid climatic zones, and pressure on water resources continues to increase year by year.

Meteorological Data for Regional Centers of the Republic of Uzbekistan (January–June 2025)

Regional Centers	2025 year							
	January	February	March	Q1 total	April	May	June	Q2 total
Precipitation (mm)								
Andijon	7.9	2.4	21.4	**31.7**	42.1	13.0	1.7	**56.8**
Bukhara	0.0	46.6	0.4	**47.0**	21.0	0.0	0.0	**21.0**
Jizzakh	25.9	38.0	65.1	**129.0**	21.6	6.6	0.7	**28.9**
Karshi	13.9	25.5	37.8	**77.2**	11.4	-	0.0	**11.4**
Navoi	2.2	44.6	5.4	**52.2**	29.0	0.7	0.0	**29.7**
Namangan	4.9	10.7	31.7	**47.3**	28.9	11.6	0.2	**40.7**
Nukus	5.2	18.4	32.0	**55.6**	12.5	0.0	15.0	**27.5**
Sama	19.3	34.5	69.1	**122.9**	35.5	0.7	5.0	**41.2**

rkand								
Syrdarya	16.7	32.5	54.1	**103.3**	6.1	7.6	0.4	**14.1**
Tashkent	26.5	39.9	59.4	**125.8**	13.3	13.8	1.7	**28.8**
Termiz	32.4	30.0	40.2	**102.6**	2.8	0.0	0.3	**3.1**
Fergana	1.1	0.0	26.0	**27.1**	24.2	10.5	17.0	**51.7**
Urgench	0.9	37.1	39.8	**77.8**	8.5	0.0	19.4	**27.9**

Figure 1. Precipitation distribution in the Republic of Uzbekistan (January–June 2025), mm

The conclusions derived from previously implemented Rainwater Harvesting (RWH) projects have significant scientific and practical relevance for the conditions of Uzbekistan. In particular, efficient use of water resources is a critical issue in the Samarkand region, where the majority of irrigated lands depend heavily on artificial irrigation systems.

Analyses indicate that one of the key factors for the successful implementation of RWH systems is the application of a systematic approach. In the context of Uzbekistan, irrigation planning should consider not only short-term outcomes but also long-term environmental and socio-economic impacts. This can be effectively achieved through the use of Geographic Information Systems (GIS) and remote sensing technologies. For instance, spatial analysis of precipitation distribution, terrain characteristics, and water flow modeling enables the identification of optimal areas for rainwater harvesting[10].

International experience highlights the importance of community participation in RWH projects. Therefore, in Uzbekistan, it is essential to actively involve farmers, water user associations, and local communities in project implementation. Otherwise, externally introduced technologies may fail to produce sustainable results in practice. Taking into account local traditions and existing water-use practices significantly enhances project effectiveness.

Economic efficiency and adaptability are also critical factors in the implementation of RWH technologies. Given that small and medium-sized farms dominate Uzbekistan's agricultural sector, it is important to prioritize affordable, simple, and scalable technologies. In this regard, micro-level rainwater harvesting systems (such as small catchment pits and contour bunds) are more suitable for local conditions and support a phased implementation strategy.

Research shows that the success of RWH technologies depends on farmers' technical capacity, financial resources, labor availability, and the income-generating potential of specific RWH methods. However, many projects fail to adequately consider local conditions, financial constraints, and market linkages. Furthermore, insufficient planning and allocation of resources for long-term management and maintenance of RWH infrastructure often undermine sustainability.

Evidence from international case studies, particularly in African countries, demonstrates that underestimating maintenance requirements can significantly reduce system performance. Failure to sustain infrastructure after construction has been a major factor contributing to the low effectiveness of irrigation projects. Micro-catchment systems, such as demi-lunes and stone bunds, require regular maintenance and, in some cases, reconstruction after heavy rainfall events.

Market infrastructure is another important determinant of success. Increased agricultural productivity does not always translate into higher income due to constraints in market access, logistics, and processing systems. Therefore, RWH technologies should be considered not merely as technical solutions but as components of an integrated system that connects farmers with markets, value chains, and agricultural services.

The sustainability of RWH systems is strongly linked to proper maintenance and management practices. In Uzbekistan, insufficient technical maintenance is already a common issue in existing irrigation infrastructure. If RWH systems are to be widely implemented, dedicated financial and institutional mechanisms for their upkeep must be established. Otherwise, the common "build-and-abandon" problem may arise, reducing long-term effectiveness.

Geographical factors must also be taken into account. In the Samarkand region, variations in topography, rainfall patterns, and soil characteristics require a spatially differentiated approach. The use of GIS and remote sensing technologies enables the identification of optimal locations and ensures more efficient resource utilization.

Under the conditions of climate change, the importance of RWH technologies continues to increase. Given the uneven distribution of rainfall in the region, these systems offer significant potential for improving water availability. Continuous monitoring of their impacts on crop yield, soil fertility, and farmers' income is therefore essential.

In general, the effective implementation of RWH technologies in Uzbekistan, particularly in the Samarkand region, requires a comprehensive approach. This includes scientifically grounded planning, continuous monitoring and evaluation, economic incentives for farmers, and the integration of GIS and remote sensing technologies. Such measures will contribute to improving water supply in irrigated lands and enhancing the overall sustainability of agriculture.

RESULTS

The application of this approach under the conditions of Uzbekistan, particularly in the case of the Samarkand region, can be effectively implemented using Geographic Information Systems (GIS) and remote sensing technologies. Based on satellite data, analyses of precipitation distribution, terrain characteristics, soil properties, and water flow patterns enable the identification of the most suitable areas for rainwater harvesting. This provides a foundation for scientifically grounded decision-making, efficient resource utilization, and improvement of the meliorative condition of irrigated lands.

Sprinkler irrigation represents a water-saving technology that has demonstrated high efficiency in irrigating winter wheat, vegetables, cereals, and other crops. Considering its effectiveness, it is advisable to include this technology in national strategies for the implementation of water-saving methods. Furthermore, sprinkler irrigation equipment should be incorporated into leasing programs for meliorative machinery. In the long term, it is recommended to establish domestic production of sprinkler irrigation systems in Uzbekistan, drawing on the experience of the Tashkent Institute of Irrigation and Agricultural Mechanization Engineers and “Texnolog” LLC[9].

In Uzbekistan, significant attention is being paid to improving the efficiency of water use and increasing both the quantity and quality of agricultural production. According to scientific estimates, the majority of water resources are consumed by agriculture. For instance, approximately 211,000 liters of water are required to produce 100 kg of wheat, around 100,000 liters for grapes, and up to 412,000 liters for cotton. Globally, more than one billion people live in regions experiencing water scarcity. In Uzbekistan, there are approximately 4.3 million hectares of irrigated land, which rely on reservoirs, main canals, and inter-farm irrigation networks for water supply[15].

Experts emphasize that declining crop yields, and in some cases complete crop failure, are directly linked to water scarcity. Therefore, the introduction of water-saving irrigation technologies is essential to mitigate this challenge and prevent inefficient water use.

At the district level, positive trends in the adoption of water-saving technologies can be observed. For example, in Ishtikhon district, the area under water-saving irrigation increased from 2,193 hectares of cotton and 248 hectares of orchards before 2019 to 3,164.5 hectares in recent years. This technology not only conserves water but also contributes to higher crop yields. Similarly, in Akdarya district, the “Pyri Milki Okdarya” farm implemented drip irrigation on 630 hectares in 2019 (including 500 hectares of cotton and 130 hectares of wheat), achieving average yields of 35–40 centners per hectare. The continued application and planned expansion of such technologies demonstrate their effectiveness and scalability[16].

International experience shows that the successful implementation of RWH systems requires consideration of not only technological but also socio-economic factors. In this regard, strengthening cooperation among farmers, local communities, and government institutions is crucial for the effective adoption of these technologies in Uzbekistan.

Overall, the integration of rainwater harvesting technologies with GIS and digital cartography plays a key role in improving water resource management, increasing agricultural productivity, and ensuring environmental sustainability. Continuous evaluation of productivity, resilience, and socio-economic impacts is essential for climate-adaptive agricultural practices.

Due to the uneven distribution of rainfall in the Samarkand region, regular monitoring of the effectiveness of RWH technologies is necessary. Sustainability assessment should incorporate stakeholders' long-term objectives, changes in ownership and management structures, and relevant performance indicators. Effective monitoring systems should be based on short feedback loops to support adaptive management.

A review of studies conducted between 1991 and 2023 indicates that research on the impacts of rainwater harvesting technologies remains relatively limited. Most studies focus primarily on crop yield, while fewer address soil characteristics and socio-economic outcomes. In Uzbekistan, comprehensive studies of this kind are still insufficient, particularly those utilizing GIS and remote sensing technologies[13].

Existing evidence suggests that RWH technologies generally contribute to increased crop yields. In the conditions of the Samarkand region, these technologies have significant potential, especially in water-scarce areas. However, their effectiveness largely depends on climatic conditions, agronomic practices, and the availability of additional resources. In some cases, positive outcomes are observed only under specific conditions or during certain years.

CONCLUSION

In conclusion, the effective implementation of rainwater harvesting (RWH) systems in Uzbekistan requires a systematic approach, the application of modern GIS and remote sensing technologies, active community participation, economic feasibility, and consideration of local knowledge and practices. These factors play a crucial role in optimizing water supply for irrigated lands and enhancing agricultural sustainability.

To ensure the successful adoption of RWH technologies in Uzbekistan, it is necessary to improve economic efficiency, account for farmers' financial and labor capacities, develop market infrastructure, strengthen state support mechanisms, and establish effective maintenance systems. These measures will significantly contribute to improving water availability and increasing the resilience of the agricultural sector.

Overall, the findings indicate that RWH technologies have strong potential for large-scale implementation by local farmers in the Samarkand region. However, their success depends on the integrated consideration of economic, technical, and organizational factors.

Rainwater harvesting represents a promising strategy for improving agricultural sustainability and ensuring water security in arid and semi-arid regions. This study highlights the opportunities and limitations of RWH systems based on investment portfolios, evaluation methodologies, and modern Earth Observation (EO) technologies. In the context of Uzbekistan, particularly in the Samarkand region, interest in RWH technologies is growing; however, their effectiveness depends on careful planning, efficient management, and strong institutional support.

Projects that are tailored to local needs, incorporate farmers' experience, and are integrated into broader agricultural development programs tend to achieve more sustainable outcomes. In contrast, initiatives that neglect post-construction maintenance, land tenure issues, and stakeholder engagement often fail to deliver long-term benefits.

To maximize the effectiveness of RWH investments, it is essential to strengthen institutional collaboration, develop targeted public policies, and promote data-driven decision-making processes. The use of geospatial technologies and participatory assessment approaches can help bridge knowledge gaps, design location-specific solutions, and ensure transparency in project implementation.

In the context of increasing climate change impacts and growing pressure on water resources, well-designed, equitably implemented, and scientifically evaluated RWH systems can play a key role in ensuring agricultural sustainability in Uzbekistan, particularly in the Samarkand region.

Overall, this study provides important insights and practical guidance for researchers, practitioners, and policymakers in advancing the development and implementation of rainwater harvesting technologies.

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