

REVIEW

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Enhancing water security through integrated storage mechanisms and rainwater harvesting for sustainable development

Joseph Omeiza Alao^{1*}, Stanley U. Eze², Geraldine I. Onyenweife³, Amarachukwu A. Ibe⁴, Oche J. Otorkpa⁵, Daniel A. Ayejoto⁶, Fahad Abubakar⁷, Momohjimoh Abdulsalami⁷ and Danga Onimisi Abdulmalik⁷

*Correspondence:

Joseph Omeiza Alao
alaojosephomeiza@gmail.com;
alaojo@afit.edu.ng

¹Department of Physics, Air Force
Institute of Technology, Kaduna,
Nigeria

²Department of Applied Geology,
Olusegun Agagu University of
Science and Technology, Okitipupa,
Ondo State, Nigeria

³Department of Geology,
Chukwuemeka, Odumegwu
Ojukwu University, Uli, Anambra
State, Nigeria

⁴Department of Physics, Nigeria
Maritime University, Okerenkoko,
Okerenkoko, Nigeria

⁵Department of Public Health,
Faculty of Health Sciences, National
Open University, Abuja, Nigeria

⁶Department of Environmental
and Sustainability Science, Texas
Christian University, Fort Worth,
TX, USA

⁷Department of Geosciences,
Confluence University of Science
and Technology, Osara, Okene,
Nigeria

Abstract

The world faces a growing water crisis, driven by population growth, urbanization, and climate change, with a projected 40% decrease in available water supply by 2030. More than 40% of the global population already experiences water scarcity, a reality exacerbated by declining natural freshwater storage, with a staggering 15,700 Billion Cubic Meters (BCM) lost between 1970 and 2019. Traditional water management strategies are insufficient, highlighting the urgent need for innovative solutions. This uniquely combined Additional Storage Support Mechanisms (ASSM) with Rainwater Harvesting (RWH) to provide decentralized, climate-resilient water solutions. It considers diverting attention away from conventional centralized systems towards a nature-driven, multi-scale storage approach that maximizes groundwater recharge, flood mitigation, and agricultural sustainability. Studies indicate that ASSM and RWH structures, such as subsurface dams, rooftop infiltration, and groundwater tanks can potentially decrease flood volume by a notable percentage, increase water storage up to 273 days, and increase aquifer recharge. The methods provide low-cost, scalable options to water-scarce areas, enhancing climate change resilience and adding to Sustainable Development Goal 6 on the provision of clean water. A risk-based simulation optimization framework showed a 46.51% increment in water allocation efficiency using surface dams, reducing water shortages by up to 87%. The findings emphasize the need for a paradigm shift in water management strategies, beyond traditional approaches, to embrace a more integrated and sustainable approach. The integration of ASSM and RWH into national water strategies will drive progress toward SDG 6 on clean water and sanitation. Investing in these technologies will not only ensure water security but also contribute to sustainable development and a healthier planet.

Keywords Storage mechanism, Dam construction, Groundwater storage, Rainwater harvesting, Management strategies



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1 Introduction

Water resource remains a fundamental resource in all sectors of life, and their availability and quality are crucial for our survival, well-being, and sustainable development. However, the world is facing numerous water challenges, including scarcity, pollution, poor management, and sustainability [1–3]. These challenges have been exacerbated by several factors, such as population growth, climate change, urbanization, seasonal variations, and unsustainable water use practices. The recent rapid population expansion alongside urbanization and industrial evolution has led to the over-extraction of groundwater resources and less infiltration of rainfall, which has significantly reduced groundwater levels, frequent borehole failures, and unpredictable water pollution [4, 5]. In addition, the growing research on water development is attributed to rapid development in water strategies across various sectors, including agriculture and industry [6, 7]. Till today, the rate of world population growth remains unpredictable, as estimations indicate that by 2030, the world will experience over 40% decrease in the available supply of water [8]. Worse still, hydrological complexity, extreme climate phenomena (droughts and floods), and chronic water scarcity are perceived as one of the greatest threats to global water security and prosperity [8–10]. Besides these fears, statistical estimations indicate that more than 40% of the world's population is already living in many parts of the world with water scarcity, while estimated data also shows that one out of every four children across the world will experience extreme water shortages by 2040 [10]. Based on these data, the need to look beyond the usual circle of water solution becomes essential.

The ongoing global water challenges are not without climatic factors and water pollution, which have taken a heavy toll on the groundwater systems. According to some remarkable studies, water scarcity is not about inadequate water availability but clean and portable water available [11, 12]. A good percentage of the available water is being contaminated by different sources, leaving a large volume of water unfit for drinking. On the other hand, the impacts of climate on flood and drought events are worrisome, which are poised to unleash prolonged and commonplace impacts on the groundwater resource [13, 14]. Climate change has been identified as one of the critical global challenges and a hotspot for groundwater potential [15–17]. Most African nations are highly susceptible to the impacts of climate change poses significant threats to environmental health, including groundwater systems [18–20]. Studies show that temperature rise has been a dominant feature, which increases from 1.5 to 2 °C approximately across Africa [21, 22]. This acceleration has shifted the goal post for the trends in rainfall, with some zones facing intense rainfall variability and high flooding, while some experience more frequent droughts, while others. Worse still, climate change influences the hydrological cycles, resulting in unpredictable groundwater behaviour and intense flood phenomena [17]. The report indicates that there is a direct exchange between flooding and rivers that usually recharge the groundwater [23–25]. These unfavourable situations have impacted the hydrological properties of a river basin, leading to groundwater pollution and a shortage of clean drinking water across the world.

Historically, humanity has invented different techniques and technologies for water storage, and ancient civilizations ingeniously developed intricate systems, such as reservoirs, terraced fields, and underground cisterns to gather and store water [26]. These beginners of early innovations set the foundation for modern water storage facilities

currently metamorphosing into ASSM, providing the needed valuable lessons and prototypes for sustainable water resource management. Today, most hierarchical nations, including some developing nations, are putting unpredictable pressure on water resources because water remains a natural resource without a substitute [27]. Therefore, storing water is crucial as a cornerstone of nation-building, especially in societies exposed to large climatic variability [28–31]. Today, many nations are suffering from inadequate water storage facilities, threatening sustainable development and even economic stability [31]. ASSM is an innovative water resource management and water enhancement for adequate water supply and sustainability. According to some remarkable studies, RWH remains a better option for storage reservoirs [32, 33]. Studies show that water storage is not limited to RWH; it also includes groundwater storage tanks, dams, etc. [6]. Currently, about 800,000 dams are being used all over the world, which is far less than the untapped excess rainwater and streams of rivers around the world [32]. This means a large percentage of rivers and rainwater remains untapped, as the majority of rainwater infiltrates the ground or runs off into rivers. Therefore, effective application of ASSM can reduce pressure on the rapid aquifer recharge needed to sustain groundwater reservoirs, especially in Cities under the current global climate variations.

While the global water crisis is widely acknowledged, existing research often focuses on traditional water management strategies like dam construction, delineation of aquifer potential, and installation of boreholes. This study addresses a critical gap by exploring the potential of ASSM and RWH as decentralized and sustainable solutions for water security. It examines the specific challenges and benefits of these approaches, highlighting their potential to address the limitations of traditional methods. The study is directed towards a paradigm of multi-scale, nature-based storage which reduces flood risks, increases aquifer sustainability, and promotes agricultural resilience. Therefore, the concepts of ASSM for strategic groundwater management and sustainability can no longer be subjected to local views. That is, ASSM needs to be a priority in the global discussion regarding water security. In response to the sixth goal of Sustainable Development Goals (SDGs), which focuses on water security to ensure everybody has access to clean and portable water [33, 34], irrespective of economic, political, educational, and social status. This article highlights the significance of the ASSM concept alongside the RWH to create a change that will improve the status of water availability and quality for sustainable development across the world. In addition, the study was motivated by some of the following research questions, such as:

- Why are there many boreholes around the world, and water scarcity keeps increasing?
- Why are there huge investments in water resource management with little yield?
- Despite the enormous geophysical investigations, the challenges of water scarcity have not been resolved.

Therefore, the need to think beyond the geophysical approach and explore the ASSM and RWH potential for adequate water security, strategic resource management, and sustainable development is quite essential in going forward.

2 Methodology

The study employs a narrative review method, synthesizing multidisciplinary literature to assess the contribution of ASSM and RWH to the strategic management of water resources. The review synthesizes evidence from the fields of hydrology, environmental science, climatology, and engineering to establish a robust framework for sustainable water solutions. Data Collection from peer-reviewed scientific articles, technical reports, and institutional documents on the topic was retrieved from the Web of Science, Scopus, Google Scholar, and ScienceDirect databases. The search terms employed for searching were: rainwater harvesting, groundwater recharge, subsurface dams, water scarcity, climate resilience, and storage support mechanisms. The search was confined to literature published within the period 2000–2024 and leaned toward studies providing empirical data, model results, or policy analysis.

The selection criteria of the studies were chosen against the following inclusion criteria: (i) Targeted rainwater harvesting systems or water storage technologies, (ii) Produced quantitative outcomes or case studies applicable to ASSM or RWH, (iii) Focused on flood mitigation, climate change impacts, or groundwater recharge, (iv) Published in English and full-text form, (v) Exclusion criteria were: (vi) Methodologically ambiguous studies, (v) Publications containing outdated or regionally inappropriate data, (vi) Non-peer-reviewed sources except as cited by valid institutions (e.g., FAO, UN, UNESCO). The data analysis-derived data were placed under thematic categorizations: storage capacity, recharge effectiveness, flood management, and policy integration. Comparative analysis was made across geographical locations (e.g., India, Hungary, Saudi Arabia) to determine performance trends and context responsiveness. This strategy provides a strong and interdisciplinary platform for assessing ASSM and RWH as effective solutions to water issues worldwide. Figure 1 presents a flowchart which captures the thematic hierarchical structure and functional diversity of water storage and harvesting systems. Each branch represents a distinct method with specific environmental and socio-economic applications, as detailed in this study.

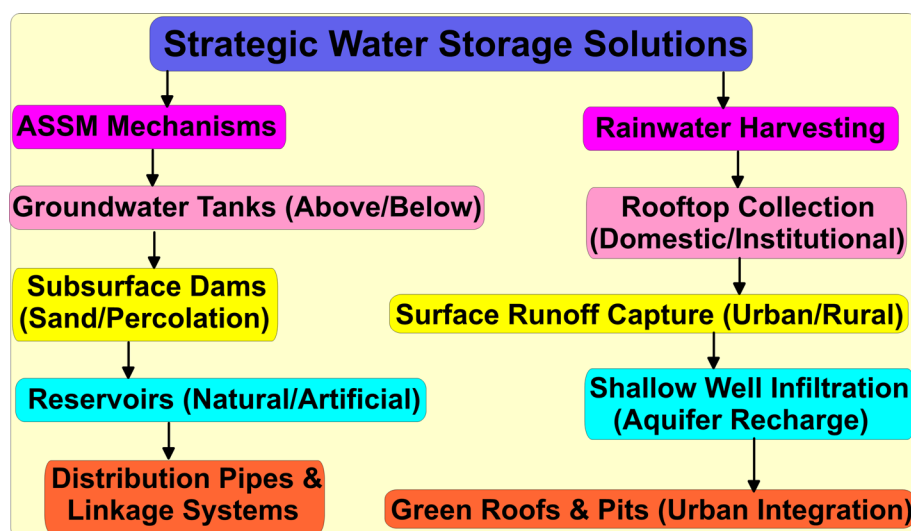


Fig. 1 The flowchart showing the hierarchical structure and functional diversity of water storage and harvesting systems

3 Additional storage support mechanism (ASSM)

Before the rapid population expansion across the world, which eventually led to an upsurge in water demand, mankind had benefited from abundant surface and ground-water reservoirs. However, the historical trajectories of human development as a result of the population explosion may have played significant roles in shaping and reshaping the water challenge across the globe, which include scarcity, pollution, and inefficient management techniques. These challenges are exacerbated by several factors, such as population growth, urbanization, climate change, and unsustainable water use practices. Addressing the challenges of water resources requires a strategic approach to water resource management that goes beyond traditional geophysical methods and explores alternative solutions such as RWH. A recent study identified ASSM alongside the water storage technologies as a key factor for water security and sustainability, which has been defined as an artificial storage option for harvesting excess water from different water sources such as groundwater, rainfall, and surface water, for subsequent beneficial use [6]. Water storage has a long historical trajectory, and it is as old as man. However, the existing storage facilities are far below the current demand, especially in developing nations [26, 35]. A broad range of groundwater potential prospecting is considered an essential requirement for the actualization of water availability in quality and quantity, but it is not enough to curb the growing global water scarcity. Several different RWH strategies can be used in different geographical settings. Many have local origins, while others have been brought in from other nations or areas.

Additional water storage support mechanisms play a crucial role in addressing the challenges of water scarcity such as water quality, accessibility, availability, and stability to ensure a reliable water supply for various purposes (Fig. 2). These mechanisms, such as reservoirs, tanks, and other storage infrastructure, are designed to capture and store excess water during periods of high precipitation and release it during times of water scarcity. While these mechanisms offer numerous benefits, they also present several challenges and require effective control measures to ensure their optimal performance

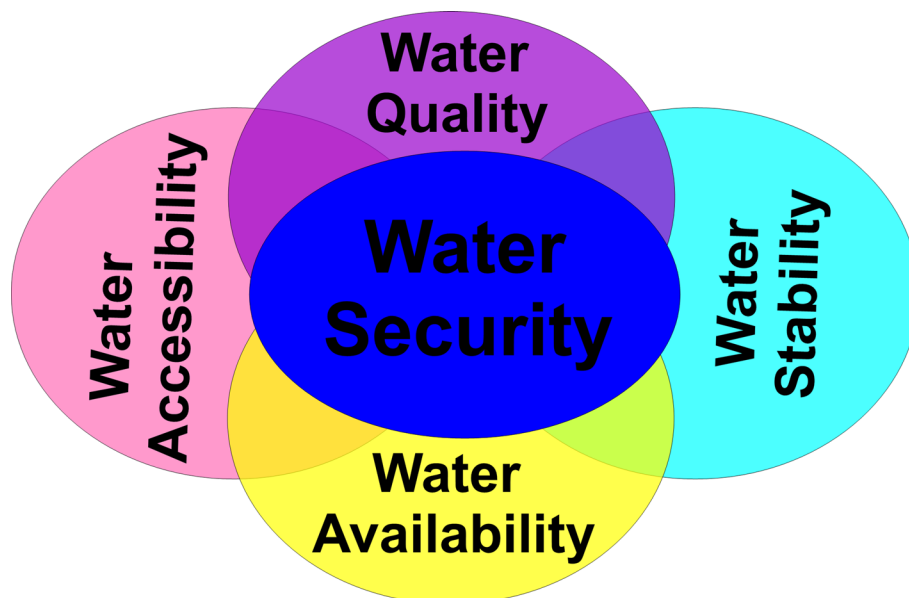


Fig. 2 Conceptual Framework of Water Security

and sustainability. One of the major challenges associated with additional water storage support mechanisms is the environmental impact. The construction of large-scale reservoirs and storage infrastructure can lead to habitat destruction, alteration of natural water flow patterns, and disruption of ecosystems. These impacts can have far-reaching consequences on biodiversity, water quality, and the overall health of aquatic ecosystems. Additionally, the inundation of land for reservoir construction can displace communities and cause social and economic disruptions. Therefore, it is essential to carefully assess and mitigate the environmental impact of additional water storage support mechanisms through thorough environmental impact assessments, habitat restoration efforts, and community engagement.

3.1 Groundwater storage tanks

Understanding the importance and roles of groundwater storage (GWS) in water resource management (WRM) is quite essential because water storage is an integral part of WRM systems that control the water flow by creating a balance between water demand and supply [26]. Groundwater storage (GWS) facilities range in shapes, sizes, and designs from household use to the public domain (Fig. 3). GWS can be designed to be underground, ground surface (on the same ground level) or above ground level (Fig. 3), depending on the purpose of construction. Water storage systems are a basic component of WRM and are a crucial part of ASSM in enhancing water security and sustainable development. Groundwater storage facilities play vital roles in delivering water services and protecting the environment from floods and droughts. A sufficient GWS with high capacity in the face of the current growing water shortages and demands alongside the extreme climate phenomena is a major worry in the coming decades [6, 27].

A groundwater dam is designed and structured in such a way that it obstructs or intercepts the flow of groundwater via aquifers, both artificial and natural, to provide underground water storage. For areas like Pakistan, where arid and semi-arid climate conditions predominate, they are an appropriate water supply arrangement [36]. Due to complicated geological circumstances, safety risks, and dam silting up, it may be an alternate option in instances when conventional surface dams are inappropriate or inapplicable. However, it may not be taken into account for recreation, universal water supply methods, or power generation [36]. Many of the issues stated above might be resolved by storing water underground rather than in surface dams. In addition to their primary function of storing groundwater, underground dams are the most effective way to stop saltwater intrusion, which is a significant offshore issue. In addition to the many benefits, there are several drawbacks, including insufficient reservoir capacity, higher operating expenses, thorough hydrogeological site studies, and aquifer testing before construction. Groundwater dams are not brand-new engineering projects; they have already been built in many locations worldwide. These kinds of buildings were historically built by ancient civilizations in Tunisia, Africa, and the Romans in Sardinia [36].

A recent study highlights the growing need for water storage due to increasing demand and climate variability [27]. It estimates that by 2025, an additional 150–300 km³ of storage capacity will be required globally, with a significant portion needing to be underground. The paper emphasizes the potential of subsurface storage, noting that aquifers hold far more water than all man-made reservoirs combined. It also points out



Fig. 3 Sample of Groundwater Storage Support Mechanism

that natural aquifer recharge can be significantly enhanced through various management techniques, including artificial recharge and controlled use. The document concludes that a combination of large and small storage systems, along with surface and groundwater recharge, is essential for sustainable water management.

Another study reviews the impact of climate change on water reservoirs in arid and semi-arid regions [37]. It highlights the importance of groundwater recharge and the role of subsurface dams in enhancing water storage. The paper presents a case study of the Al-Ghat Dam in Saudi Arabia, where a small earthen dam with injection wells is used to replenish groundwater. The study found that the dam has a storage capacity of $1.0 \times 10^3 \text{ m}^3$ and a drainage area of 43 km^2 . The paper also emphasizes the need for more research on the effects of climate change on water resources in arid regions, particularly on sedimentation rates and the development of adaptive management strategies. For instance, the rate of rainfall and drought in arid and semi-arid zones has suffered severe shortages due the extreme climate phenomena. Some remarkable studies examined the positive and negative impacts of GWS in the pursuit of sustainable WRM [38]. The results show that the positive side of GWS reservoirs scores high and suggest

that the GWS reservoirs should be adopted and incorporated into the regional development plans.

A study explores the design, functions, and challenges of reservoirs, focusing on their water storage capabilities [39]. It highlights the concept of dependable yield, which represents the maximum constant water draft a reservoir can sustain without failing during a historical drought. The study provides examples of dependable yield calculations for Lake Corpus Christi, demonstrating how it can be affected by different drought periods. Furthermore, the document discusses the impact of sedimentation on reservoir lifespan, noting that siltation is a major challenge for reservoirs worldwide. It presents the Hjulström-Sundborg diagram, which illustrates the relationship between sediment size, current speed, and sediment movement. The document also examines water quality issues, including the formation of thermal stratification and the release of nutrients from sediments. Finally, the study explores the impacts of reservoirs on rivers, highlighting the alterations in flow patterns, channel erosion, and water quality downstream. It emphasizes the need for careful management to balance competing demands for water supply and flood control, especially in the face of increasing population, agricultural needs, and climate change.

The Global Water Partnership (GWP) perspectives paper highlights the growing global water storage gap, emphasizing the need for a new integrated approach to water storage management [40]. The paper presents quantitative findings on the decline of natural storage, including glaciers, wetlands, and snowpacks, and the limited growth of built storage, particularly large dams. It estimates a net loss of 15,700 BCM of terrestrial freshwater storage between 1970 and 2019, excluding the Antarctic and Greenland ice sheets. The study argues that a shift from viewing storage as individual facilities to a service-oriented approach is crucial for effective management. It emphasizes the need for better inventorying of storage, understanding the effectiveness of nature-based solutions, and developing tools for integrated storage planning and operations. The paper concludes by advocating for innovative financing mechanisms and inclusive stakeholder engagement to address the growing water storage gap and build resilience for sustainable development.

In addition, RWH is not just a powerful ASSM; it remains a sustainable way to control stormwater runoff and lower the danger of flooding because it is a potent weapon in the battle against urban floods. RWH systems assist in lessening the effects of heavy rainstorm events, which are occurring more frequently as a result of climate change, by gathering and storing rainwater from rooftops and other surfaces [41]. The efficiency of RWH systems in urban settings has been emphasized by recent studies. For example, studies carried out in Sicily, Italy, showed that RWH tanks might dramatically lower flood levels in residential areas that are vulnerable to flooding [41]. These systems efficiently retained rainfall by using collected rainwater for non-potable uses, such as flushing toilets, which lessened the strain on urban drainage systems. Moreover, RWH systems can be linked to urban design to develop decentralized water management solutions. By turning every home into a miniature water production facility, cities can become more flood-resistant and less dependent on centralized water delivery systems [41]. This strategy encourages communities to actively participate in water management by reducing the risk of flooding while simultaneously promoting social entrepreneurship and innovation. RWH has advantages that go beyond preventing flooding [42]. These

systems contribute to the replenishment of nearby aquifers by allowing rainwater to seep into the ground, guaranteeing a sustainable supply of water in the future. Furthermore, RWH can enhance water quality by lowering the quantity of contaminants that enter waterways during periods of intense precipitation.

Several studies have been carried out to examine the effectiveness of RWH, including a recent study that investigated the efficiency of RWH systems in minimizing the volumes of flood in a residential area, in Palermo, Italy [41]. The study simulated the performance of RWH tanks in 408 single-family houses using historical rainfall data from 2002 to 2008. The results show that RWH systems can significantly reduce flood volumes, especially for rainfall events of low and medium (up to 5 cm) depth. However, for severe rainfall events, the contribution of RWH tanks to the volumes of flood reduction is highly limited due to insufficient storage capacity. The study also found that RWH systems can reduce flooded areas by up to 100% for small rainfall events and by 35% approximately for rainfall events with up to 50 mm depths. The study concludes that RWH systems can be an effective tool for mitigating urban waterlogging problems, but further analysis is needed to optimize tank size and address the limitations of RWH systems for severe rainfall events.

In a similar study, the effectiveness of RWH systems in mitigating urban flooding in arid regions, specifically in Bahrain, was investigated [42]. The study utilizes a 2D hydrodynamic model to simulate flood scenarios with varying rainfall intensities. The study found that RWH systems significantly reduced flood volume, particularly for low-intensity rainfall events. The rainwater retention index, a measure of flood reduction, was higher in areas with high urban density. The study also found that the size of the RWH tank played a crucial role, with larger tanks leading to greater flood reduction. The research highlights the potential of RWH systems as a flood mitigation measure in arid areas, particularly in regions lacking proper stormwater infrastructure. However, the study emphasizes that the effectiveness of RWH systems is dependent on factors such as rainfall intensity, urban density, and tank capacity. In conclusion, rainwater harvesting is a versatile and impactful strategy for reducing urban flooding. By harnessing the power of rainwater, cities can better manage stormwater runoff, protect their infrastructure, and promote sustainable water usage. As climate change continues to increase the frequency and intensity of rainfall events, the adoption of RWH systems will be crucial in building resilient and flood-resistant urban environments.

3.2 Rainwater harvesting

Rainwater Harvesting (RWH) is an artificial way of collecting and storing rainfall for subsequent reuse (Fig. 4). RWH has a long history with farmers to increase crop yields while reducing erosion in the process. RWH, alongside the water storage technologies, is a key factor for water security and sustainability [6]. RWH can be practised through roofing dam collection, which has been a major source of agricultural water supply in many parts of the world [43–48]. Water resource availability is either limited or seasonal, which has spurred the water scientists and related fields to keep on searching for alternative solutions to the shortage of water [6]. Maximizing water usage and preservation as a natural resource could minimize the challenges of water shortage across the world [49]. RWH technology has been identified as one of the promising options to resolve global water shortage [49, 50], which preserves the environment and water resources

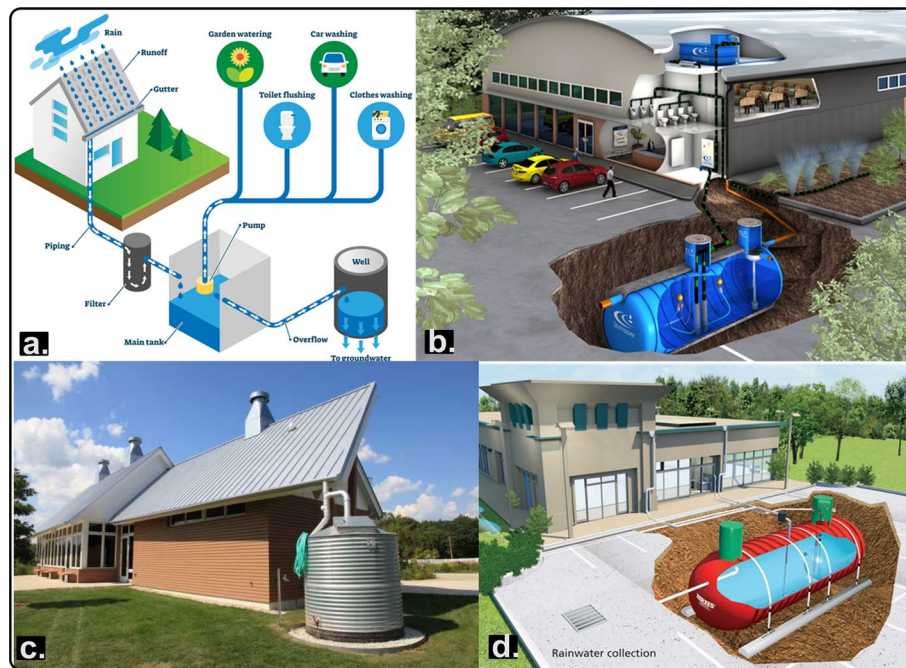


Fig. 4 Photographs of a Rooftop Rainwater Capturing System [56]

while reducing the impacts of pollution, flooding, and climate events. In India, a study was conducted to evaluate the hydrologic impact of RWH structures in the Arvari River catchment as an alternative water supply for possible reuse, especially for agricultural purposes [49]. Four RWH structures were utilized for possible surface runoff volumes as potential recharge, which was estimated over the catchment area. The results showed that about 12,000 m³ was the minimum stored volume in Jhiri Johad Bandh stored for the year 2011, while about 50,000 m³ was experienced in Sankara Bandh stored in the same year. The study noted that the RWH structures could store water for up to 273 days or more, which predicts a great potential for RWH applicability.

However, RWH technologies have not been successful in some other parts of the world. According to a remarkable in Ethiopia, more than 90% of the national food supply relies on rainfall [51]. Therefore, rainfall failure means a great loss of the national food supply, which will always lead to a massive national food deficit. To avoid the challenges, Ethiopia's National government established a national strategy for implementing various RWH technologies [47]. In 2019, a study was conducted in the Somali region of Kebri-beyah district, Eastern Ethiopia, to identify the determinants of the adoption of RWH technologies in the district [50]. The results study revealed several determining factors for the adoption, such as financial access, educational level, service extension, and approaches of RWHT in the Kebri-Beyah district. However, poor site selection and design for the RWH structure were established as key factors affecting the RWH technology adoption in the district. Therefore, understanding the factors controlling the RWH technology adoption is essential to the effective implementation of the RWH project. According to the study, these determinants must be wisely considered and resolved adequately for successful RWH technology adoption in Kibri-Beyah and similar regions in the future.

The oldest form of RWH is through the rooftop medium. However, the environmental impacts of rooftops and the long-term potential of RWH alongside the shallow well infiltration, which is a remote-scale inexpensive answer to ease the water scarcity. In Hungary, a field experiment was conducted using funneling as a medium of rainwater collection from the rooftop of a household into a shallow dug well, connected to a porous unconfined aquifer [52]. The study also monitors the changes in ground thermal systems, groundwater levels, and hydrochemical footprints to determine the qualitative and quantitative factors of this technique to predict the long-term physico-chemical impacts of the percolated water within the ambient groundwater over 600 days. The results showed that about 60.616 m³ of precipitation percolated, which could significantly obtain an improvement in water quality. Investigation shows that the contents of dissolved substances decreased by 35–88% after the infiltration commenced, which further decreased by 35–96% towards the end monitoring period. On the other hand, the concentration of heavy metals such as Zn, Sr, Cu, Mn, Ba, and Al was found to be increased by 1.9–48.2 times higher in roof runoff than in the precipitation. This information indicates the effectiveness of rooftop RWH and the environmental impacts, which can be implemented across the world, especially in porous unconfined aquifers.

Several studies have been carried out to examine the effectiveness of RWH, including a recent study that analyzes the effectiveness and financial viability of rainwater harvesting systems (RWHS) in two academic dormitories, one in Poland and one in Slovakia [53]. The study uses a simulation model to assess water savings for different tank capacities. The results show that RWHS in the Slovak dormitory is financially profitable, with a positive Net Present Value (NPV) and a discounted payback period of less than 30 years. However, the Polish dormitory's RWHS is not financially viable due to lower water savings and higher investment costs. Sensitivity analysis reveals that the Slovak dormitory's RWHS is less sensitive to changes in investment costs and water/sewage prices compared to the Polish dormitory. The study highlights the importance of considering both technical and economic factors when evaluating RWHS implementation.

A study investigates the potential of rooftop rainwater harvesting coupled with shallow well infiltration (RRWH-SW) for groundwater replenishment in the Danube-Tisza Interfluvium (DTI) region of Hungary [52]. The study found that over 20 months, 60.616 cubic meters of rainwater were infiltrated through a shallow well, resulting in a significant improvement in groundwater quality. The water level in the infiltration well showed a direct response to precipitation events, indicating effective recharge. However, clogging of the well bottom was observed, highlighting the need for regular maintenance. The study also found that rooftop-collected water was enriched in certain trace elements, particularly zinc, which exceeded the limit value for groundwater. However, zinc concentrations decreased over time, suggesting that this contamination risk may be manageable. Overall, the study demonstrates the potential of RRWH-SW as a local-scale solution for groundwater replenishment but emphasizes the importance of careful design, monitoring, and maintenance to ensure its effectiveness and minimize environmental impacts.

The impact of rainwater harvesting structures (RWHS) on groundwater recharge in the Arvari River catchment, India, was investigated, which shows that RWHS significantly contribute to groundwater recharge, with potential recharge volumes varying based on rainfall and structure characteristics [49]. The study analyzed four RWHS,

finding that the Sankara bandh stored the most water (50,000 m³), while the Jhiri Johad had the longest water storage duration (273 days). The study also observed a positive correlation between RWHS density and groundwater table rise, particularly in the upper and middle reaches of the catchment. The authors conclude that RWHS are a valuable tool for improving groundwater recharge in the Arvari River catchment, particularly during periods of low rainfall. They recommend further research to better understand the impacts of RWHS on catchment hydrology and stakeholder needs.

Another study investigates the determinants of rainwater harvesting technology (RWHT) adoption in the Kebri-Beyah district, Ethiopia [50]. Using a Probit model, the study found that education level, training, family size, extension service, and extension approach significantly influence RWHT adoption. Specifically, higher education levels, participation in training, larger family sizes, and access to extension services are positively associated with adoption. Participatory extension approaches were also found to be more effective than top-down approaches. The study also found that market distance, slope, and soil conditions were not significant determinants of adoption.

A recent review examines the observed and projected impacts of climate change on water security in global drylands [54]. It highlights that drylands are already experiencing increased aridity, changes in rainfall patterns, and declining soil moisture and terrestrial water storage. These changes are projected to worsen, with increased drought frequency, severity, and duration, leading to a potential expansion of dryland areas. By 2050, under a business-as-usual scenario, up to 1.3 billion people in drylands could be exposed to water stress, drought intensity, and habitat degradation. The review emphasizes the need for integrated water resource management (IWRM) to address these challenges, including efficient water management, technological advancements, and equitable access to water resources. In a similar capacity, a comprehensive review of 83 literature papers on RWH provides a wide range of contextual understanding of the effectiveness of RWH for some domestic uses in addressing socio-economic challenges for water security and sustainability [55]. It was noted that the direct usage of rainwater is a societal norm, which has generated a significant number of benefits, and it must be given a chance in water resource management perspectives. However, RWH technology was identified as the sole domestic and non-domestic water source in some localities. Future efforts were suggested to advance RWH technology through integrated systems instead of isolated rainwater preservation. RWH technology can be very useful in water-stressed areas due to drought and arid environments to promote water security and sustainability, especially in a difficult (isolated) terrain such as military bases, institutes, camps, etc., where installations with the following issues. In future research, RWH should focus on three key areas: (1) gathering more empirical data on system operation to enable better modeling that considers the multiple objectives of RWH systems; (2) investigating maintenance aspects and how they may affect the quality of collected rainwater in the future to boost trust in rainwater use; and (3) researching the most effective ways to target institutional and socio-political support to enhance system efficacy and community acceptance.

3.3 Dam water storage construction

Dam water storage is a water storage option constructed to constrain the flow of water movement [36], which can be done either inside rivers (traditional surface dams) or

below ground level (groundwater dam). In the last few decades, the level of groundwater has significantly declined in many parts of the world, as a result of unfavourable climate events and human activities [52]. These storage systems are highly efficient and appropriate for groundwater development, especially in regions where harsh climate conditions dominate. Figure 5 is a typical example of a subsurface dam. The storage capacity of a dam depends on the purpose. Generally, small dams have at least 10,000 m³ storage capacity on an average of 500 m length, 50 m width, and 4 m depth [57]. However, larger dams may extend from 200 to 500 m in width, and 5–10 m in depth or more, have a width of 200–500 m or more. This will increase the dam storage capacity from 100,000 m³ to 1,000,000 m³ [57]. Dams have been widely studied to enhance groundwater storage capacity after strong advocacy by the United Nations Agenda 21 in 1992 [58]. The study applied a risk-based simulation optimization framework to determine maximal water allocation with surface dams to curb to effect of unfavourable climate conditions on water resources [58]. The modeled framework, which makes use of MODFLOW UnStructured-Grid was developed to convey water away aquifer through a sloping underground channel due to gravity force. The results show that the developed framework was significantly enhanced by a 46.51% increment and reduced the water

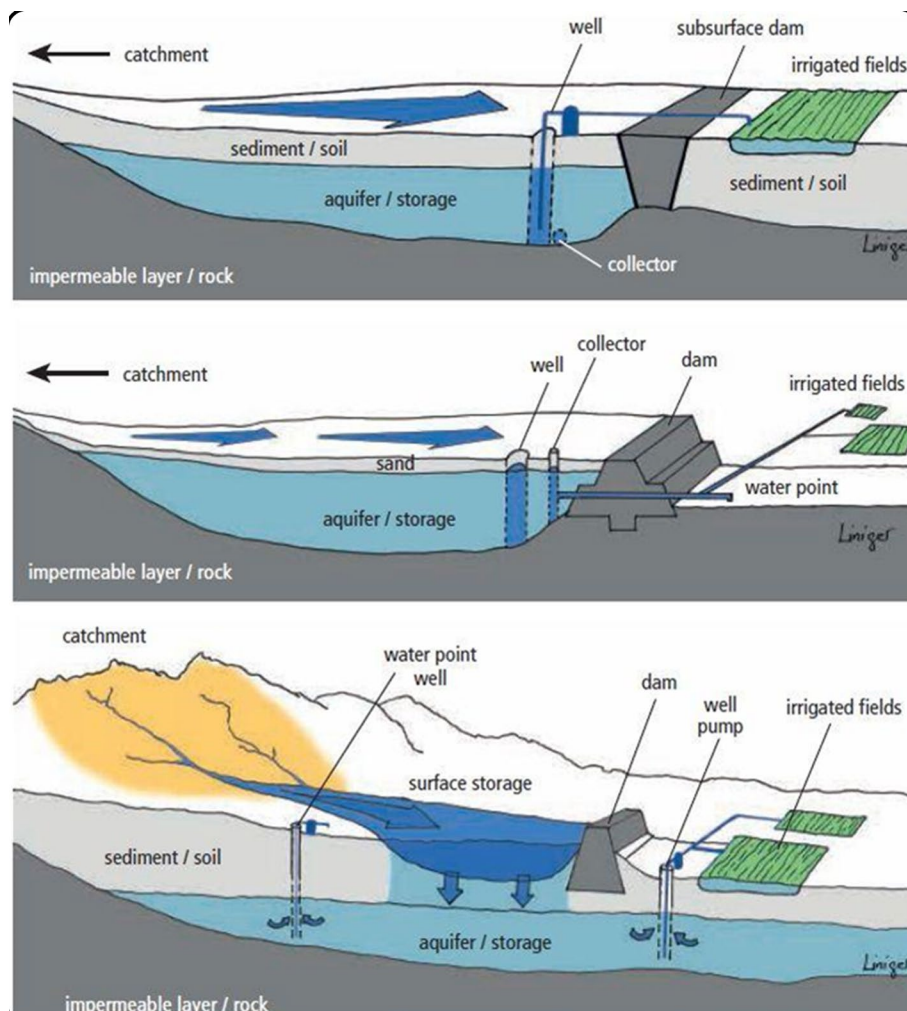


Fig. 5 Longitudinal section of (top) a subsurface dam, (middle) a sand dam, and (bottom) a percolation dam [57]

shortage from 87%, 75%, and 32% to 53%, 32%, and 0% in dry, normal, and wet periods, respectively.

The method of water storage via dam systems has been adopted in many parts of the world, especially in Brazil, India, Namibia, Ethiopia, Sardinia, Kenya, Montenegro, Burkina Faso, Austria, Turkey, Greece, Mexico, United States, China, Afghanistan, Korea, Japan, Libya, Tunisia, and other parts of the world [59–64]. As of 1990, at least five underground dams subsurface dams had been constructed with high storage capacities of about 1,000,000 m³ to 5,000,000 m³ had been constructed by grouting method in Korea, while five subsurface dams in Japan, and four were developed in India with plastic brick, stone masonry, and other materials for agricultural development [63–65]. In 2001, an underground dam with 20,000,000 m³ storage capacity was developed in Japan [65]. Studies have shown that groundwater dam systems storing water can reduce the loss of water due to evaporation and contamination risk. This is because underground dams would not breed parasites, and the impact of extreme climate change can be minimized significantly [36]. This research paper explores the concept of groundwater dams, structures designed to intercept and store groundwater. It provides a historical overview of their development, highlighting examples from various countries like Japan, Ethiopia, and Brazil [36]. The paper classifies groundwater dams into two main types: underground dams and sand storage dams. In addition, it emphasizes the advantages of groundwater dams, including reduced evaporation losses, minimal silting, and environmental friendliness. However, it also acknowledges limitations such as smaller reservoir capacities and higher maintenance costs. It concludes that groundwater dams offer a viable alternative water supply solution for arid and semi-arid regions, particularly in countries like Pakistan.

In a similar capacity, a research work investigates optimal water allocation from subsurface dams using a risk-based optimization approach [58]. The study focuses on the impact of uncertainty in rainfall and demand on water allocation strategies. The study developed a stochastic optimization model that considers both economic and environmental factors. The quantitative findings demonstrate that the proposed risk-based approach significantly improves water allocation efficiency compared to traditional deterministic methods. The model effectively balances water supply and demand while minimizing the risk of water shortages and maximizing economic benefits. The study highlights the importance of incorporating uncertainty into water resource management decisions to ensure sustainable and resilient water systems. In summary, water storage through dams has been identified as a suitable water supply for irrigation purposes and agricultural development.

4 Challenges and control

The challenges facing the implementation of ASSM require controlled services of different fields of study, such as geophysics, geology, engineering, phenomenology, climatology, weather forecasting, environmental studies, and other related fields. This is because while rooftop surfaces are generally cleaner than sidewalks, parking lots, and other impervious surfaces, rooftop runoff can contain significant amounts of contaminants such as heavy metals and nutrients. The sources of pollutants in rooftop runoff include precipitation (i.e. wet deposition), atmospheric pollutants, and atmospheric contaminants [42, 66]. Therefore, the integrity of harvested rainwater depends largely

upon the materials used to construct the RWH system and the environment in which it is located [42]. A few potential challenges, such as climate activities, pollution threats, linkage problems, treatment service, distributions, and maintenance, were selected for discussion on various water storage options to protect the future of water resource management and sustainability.

4.1 Climate activities

Understanding unfavourable extreme climate change and its implication on surface and groundwater systems is a critical part of effective ASSM for sound long-term water security and sustainable development. However, predicting the behaviour of climate variation is a difficult task due to seasonal variation [67]. There are huge gaps and uncertainties in predicting the future climate of surface and groundwater systems [68, 69]. According to a remarkable study in India, many irrigated areas in India would require a generic scientific approach against climate change due to the projected climate variations between 3.5–5% by 2025 and 6–8% by 2075 [70]. This implies a rapid decline in groundwater level systems. Another study projected the evaluation of groundwater potential as a good approach to groundwater availability, especially in arid zones and developing nations, where the upper cretaceous aquifer vulnerability was assessed [71].

Based on the information gathered from remarkable literature, the need to shift thinking around water security and sustainable development is quite essential. Though, there have been several calls for better-built facilities for water security and sustainability [72–74]. However, the study shows that effective delineation of aquifer-promising zones in conjunction with a broader range of water storage and strategic water resource management of both surface and groundwater is a preferred option going forward [6]. ASSM and RWH augment the implementation of water management by lessening dependence on surface supplies, improving recharge to groundwater, and providing seasonal certainty. Combined, these allow climate variability resilience, maximize resource utilization, and sustain urban and agricultural long-term sustainability. However, indications show that there is little attention to what an integrated water storage mechanism approach for WRM would look like in sustainable development practice. Every water storage facility has its challenges and benefits in terms of socioeconomic sustainability, health implications, stakeholder/institutional requirements, environmental impacts, and technical feasibility [31]. These Factors require a generic consideration wisely within the purview of human, cultural, biophysical, and political contexts.

In addition, water storage facilities and distribution pipe networks can significantly impact the effects of climate change. This is because climate change can exacerbate the challenges of maintaining the quantity and quality of water stored by damaging infrastructures and altering the treatment needs for source water, which may cause direct contamination of water stored during flooding or other events [75]. Studies have shown that the variation in temperature and precipitation patterns as a result of climate change can alter or tame the volume of water availability, ASSM, which makes it necessary to enhance and expand water storage capacities [76, 77]. Water storage is considerably more important in areas that are suffering from protracted droughts. During dry spells, having enough storage space helps lessen the effects of water scarcity. Enhanced River Flow Variability: Increased river flow variability, including drought and flooding, is a result of climate change. The surface water supply's dependability is impacted by this

unpredictability. Changes in river flow patterns have a direct effect on distribution pipes. It is crucial to make investments in strong distribution pipe infrastructure to adapt to climate change. Pipes can be made more resilient to severe weather conditions and guarantee a steady supply of water by being upgraded and maintained. In conclusion, to guarantee water security for communities around the world, climate change demands better development of water infrastructure, including enhanced storage facilities and robust distribution networks.

4.2 Contamination and control

One of the major significant challenges of RWH and ASSM is the management of water quality within storage infrastructure. Stored water can be susceptible to contamination from various sources, including agricultural runoff, industrial discharges, and urban pollutants [7, 33, 78]. As a result, maintaining water quality within storage facilities is critical to ensuring the safety and suitability of the water for various uses, such as drinking, irrigation, and industrial processes. Effective control measures, such as regular monitoring, water treatment, and source water protection, are essential to safeguarding water quality and minimizing the risk of contamination within storage infrastructure [79–82]. In addition to this, the processing of capturing water for storage can be highly susceptible to contamination if necessary steps are not taken to curb the environmental factors. Studies have shown that landfill leachate plumes remain one of the most popular external contaminants [83, 84]. Adequate control of environmental contaminants is crucial.

One of the potential challenges of ASSM is the potential water contamination through the distribution pipe linkage [6], where the water flowing through the pipe interacts with the environment [85]. When the water flowing through pipes interacts with a polluted environment, the water supply to the communities gets contaminated [86–88]. Some studies examined the leakage rate and estimated that about 23% of the average water leaked in water-distributed networks in Europe [89]. That is, 77% of water distribution networks are efficient statistically. Leakage poses a phenomenal threat to water distribution and maintenance companies due to pollutant infiltration. In recent times, several investigations have been conducted to acquire data from pressure transducers and flow meters along pressurized water networks [90], to establish the relationships between leakage and pressure [91]. Efforts to mitigate the challenges of water leakage have suffered significant setbacks due to the huge time spent detecting the location of the leakage. Many efforts and approaches have been put in place to find lasting solutions to the pipe leakage challenge; however, it has not reached the required control.

Water storage facilities and distribution pipes can be significantly affected by external contaminants such as leachate plumes, wastewater, oil spillage, and domestic sewage through pipe leakage. Internal corrosion of pipes can lead to toxic metals such as copper and lead, which can potentially leach into the water facilities, imparting staining fixtures, a metallic taste, minimizing hydraulic carrying capacity and resulting in clogs and leaks eventually [35, 92, 93]. For instance, chemical contaminants (chemical spills) can gain access to water storage facilities through air pollution and surface-water runoff into open reservoirs or accidental chemical spills during transport close to water storage facilities can be a threat to public health if the chemicals are highly concentrated and toxic [67, 94]. Absolute control of water leakage or contaminants infiltrating into water storage and distribution facilities can be a difficult task, but it is possible. To address

these challenges, regular treatment practices such as disinfectant residuals, spot flushing, physical integrity, and draining operations are required to ensure portable and clean public water systems (PWSs) [95].

Maintaining a disinfectant residual in the public water distribution system can protect against microbial contaminants because the residual can serve as an indicator of the system to upset and helps limit the development of heterotrophic *Legionella* and bacteria within the water distribution pipe network [35]. On the other hand, PWSs can adopt spot flushing programs in dead-end piping or low-water use regions to restore disinfectant residuals and flush out the stagnant water. By this, public water circulation systems would be improved through the addition of mixing devices to storage facilities enhancement [95]. Furthermore, the replacement of pipe facilities, especially those made of materials with high chlorine demand such as cast iron can improve chlorine residuals, which will maintain the quality of water in ASSM and distribution pipes involves addressing physical, chemical, and microbial factors to ensure reliable and safe water supply. In conclusion, developing a water sensor leakage detector, which works on the principle of pressure transmission to checkmate water flow through the pipes, may be a preferable option in going forward.

4.3 Linkage and control

Systems for storing water tanks are essential for managing water supplies, particularly in areas that are vulnerable to floods and droughts. Nevertheless, the influence of these systems on flood management and the strategies to manage them are frequently disregarded [96]. For disaster mitigation and water management to be effective, these factors must be understood. By collecting and storing extra rainfall during intense downpours, water tank storage systems can dramatically lower the risk of flooding. The amount of stormwater runoff that causes urban flooding can be decreased by releasing this stored water gradually or using it for non-potable uses like industrial activities or irrigation. According to studies, combining rainwater harvesting systems with water tank storage can successfully lessen the effects of flooding in metropolitan areas [96]. Several strategies can be used to efficiently manage water tank storage systems. Tanks must have routine maintenance and inspection to maintain their integrity and stop leaks. To prevent contamination and evaporation, storage water should be properly sealed and covered [97]. Filtration systems can also be used to keep water clean and stop dangerous bacteria from growing. For effective tank management, temperature and water level monitoring are also essential. It is possible to install automated devices to control water flow and preserve ideal storage conditions [98]. Stored water can be utilized to augment the water supply during dry spells, guaranteeing a steady and dependable supply of water for a range of purposes [99]. In conclusion, by collecting and storing extra rainwater, water tank storage systems significantly reduce the risk of flooding. To ensure effective water use and preserve water quality, these systems must be properly managed and controlled. The advantages of water tank storage can be optimized by putting in place appropriate sealing, monitoring, and routine maintenance procedures, which will help with catastrophe resilience and sustainable water management. In conclusion, absolute control of water leakage is a difficult task but it is possible. Developing a water sensor leakage detector to monitor the flow of water through the pipes may be a preferable option and

the way forward. The sensor could be developed to work on the principle of pressure transmission.

4.4 Distribution and maintenance

The distribution of storage water in a large municipal utility system is quite challenging depending on the regional population growth [100, 101]. The challenges of water storage distribution such as pipe linkage, inadequate hydrogeological site investigations, poor attitude, ineffective or lack of aquifer tests before construction, and high cost of operation [6]. In the next 10 to 20 years, the challenges of the water may not be the availability of water in quantity and quality but distribution and maintenance due to high levels of indiscipline, especially in developing nations [94]. As a result, a shift away from the usual water challenge-oriented is an essential focus on the efficiency, and demand use of water. The world must shift the goalpost of thinking about how best to take more water from the existing stressed or over-tapped surface and groundwater to how best the existing water resource can be managed in a way that allows optimal delivery of high-quality water. The maintenance of water facilities is essential to meet the endless demands of uninterrupted water supply service with high quality [102–104]. Nevertheless, attacks such as terrorist attacks, citizen protests, and cyber-physical attacks on water distribution networks pose significant threats and risks to water distribution and maintenance. In resolving these issues, careful measures and consideration of appropriate tools and methodologies are required [104]. Water distribution networks need maintenance and investment to ensure sustainable service.

4.5 Environmental and socio-economic implications of ASSM

The environmental implications of ASSM span beyond the application of ASSM, such as subsurface dams, underground storage tanks, and RWH systems, which significantly decrease environmental degradation. However, flood mitigation, aquifer recharge, lower evaporation losses, and pollution control remain the pinnacle consequences of ASSM and RWH. RWH schemes minimize stormwater runoff, which significantly reduces flood risk and conserves aquatic ecosystems [96, 99, 105]. Infiltration wells and ground water dams increase ground water levels, maintaining quality water and minimizing salinity, while subsurface storage leads to lower loss of water in comparison with surface reservoirs, conserving freshwater. The interception of runoff is by ASSM to prevent pollutants from entering rivers and aquifers [106], particularly in industrial and urban areas. However, the massive infrastructure of ASSM and RWH can disrupt ecosystems and necessitate sophisticated environmental impact assessments to prevent loss of biodiversity. In addition, the socio-economic implications of ASSM brings with it creative dividends to communities, particularly in water-scarce areas for agricultural productivity, which provides assurances for irrigation during drought periods, increasing crop yields and food security [27]. It is also a cost savings as a result of decentralized water systems, which eliminate dependence upon costly centralized water supply and treatment infrastructure. This decentralized water management encourages ownership, adaptability, and innovation, particularly for rural and semi-urban communities. However, it usually accompanied with challenges such as up-front capital expenses, technical experience, and maintenance requirements, which must be overcome through policy intervention, training, and stakeholder mobilization to attain long-term success [51, 55].

5 Discussion: sustainable water management: global perspectives, practices, and impacts

Based on the compiled literature, by 2030, a projected 40% decrease in available water supply, with over 40% of the global population already struggling with water scarcity, a reality that will only worsen without decisive action. While traditional water management approaches have their place, the numbers project a clear picture of the need to think beyond the box and embrace innovative solutions. The data paints a stark picture of our current reality with natural freshwater storage declining by a staggering 15,700 BCM between 1970 and 2019. This figure refers to the total global loss of natural freshwater storage between 1970 and 2019, which involves declines in wetlands, glaciers, and underground aquifers. It is a staggering volume that highlights the urgency of adopting sustainable water storage solutions like RWH and ASSM. The ASSM and RWH approaches offer a path towards a more sustainable future, as demonstrated by real-world examples. A single RWH structure successfully stored 12,000 m³ of water, showcasing the potential of this technology to provide a significant water source in India. Rainwater infiltration through a shallow well yielded 60.62 m³ of water, proving the effectiveness of RWH in replenishing groundwater in Hungary. These numbers highlight the potential of ASSM and RWH to address the water crisis. It presents a decentralized approach to water management, empowering communities to take control of their water supply and reduce reliance on centralized systems. This will reduce over-extraction of groundwater, inadequate infiltration, and anthropogenic contamination, i.e., landfill leachates and dumping of industrial effluent, accentuate the crisis. Climatic vagaries such as floods and droughts also interfere with hydrological cycles and groundwater recharge.

In global perspective of RWHs: RWH has ancient roots but contemporary relevance. India, Brazil, Mexico, and Australia employ RWHs everywhere to counteract water scarcity [107, 108]. RWHs supply drinking water for arsenic-contaminated regions of Bangladesh. Singapore employs RWHs in its city water policy, and Botswana employs them in desert areas for schools and clinics [109]. For instance, RWH structures store water for up to 273 days, supporting agriculture in India [49]. In Hungary, rooftop RWH coupled with shallow wells improves groundwater quality, while Singapore Integrates RWH into its urban water strategy. Botswana applies RWH in arid zones for schools and clinics, and Bangladesh applies RWH to provide safe drinking water in arsenic-prone areas. These examples demonstrate RWH's adaptability across climatic zones and socio-economic contexts to be a decentralized, adaptive, and sustainable option in these instances. However, RWHs have various strengths, such as: (a) Reducing the load on groundwater and municipal supply, (b) Flood and soil erosion mitigation, (c) Enhanced farm productivity. (d) Encourages environmental sustainability, and (e) reduces energy and water charges. And yet RWH is unlimited; these are: (a) High installation cost at the beginning, (b) Rainfall pattern dependent, (c) Small storage capacity, (d) Prone to contamination if not well maintained, and (e) Technical expertise and constant maintenance required [110]. The types of RWH practice such as: (a) Rooftop RWHs, which harvest rain from roof to tanks or recharge pits, (b) Surface runoff harvesting, which harvest water from paved or open surfaces, (c) Subsurface dams, which harvest water below ground to minimize evaporation, (d) Green roofs and infiltration pits, which encompasses integrate into urban design, and (e) Direct-pumped systems, which encompasses pumps in water

distribution [111], play an important roles. The RWH has cross-sectoral advantages, such as (a) Rainwater supply in drought conditions, (b) Recharge of groundwater and improvement of quality, (c) Mitigates urban flooding and stormwater flow, (d) Supports irrigation and food security, and (e) Promotes community resilience and environment awareness [108]. Rainwater treatment is also extremely significant and can be treated physically like filtration (sand, gravel, membrane) and sedimentation and first-flush diversion. Rainwater treatment is also treated chemically using chlorination or ozonation to kill pathogens and pH correction, and heavy metal removal. Biologically, rainwater is treated by biofilters or slow sand filters and new methods like bacteriophages and predatory bacteria to remove pathogens [112]. However, rainwater treatment also varies with use, e.g., drinking water involves stronger processes than irrigation. The RWHs also play a strong role in groundwater recharge. RWH facilities hold water for as long as 273 days, replenishing aquifer levels, according to Indian studies [113]. Roof-top RWHs and shallow wells in Hungary maintained groundwater levels and quality. Subsurface dams eliminate evaporation and ensure aquifer sustainability [114]. This study takes an interest in accentuating the point that ASSM and RWHs together form a strategic direction towards recharging groundwater, particularly in arid and semi-arid areas.

In addition, the major consequences of ASSM and RWH are the massive boost of agricultural produce and flood mitigation. RWH and ASSM offer a powerful solution to enhance agricultural productivity and mitigate flooding. RWH captures rainwater, reducing runoff and replenishing groundwater. This stored water can be used for irrigation, minimizing reliance on scarce water resources and ensuring consistent crop water supply, massive ASSM such as dams, reservoirs, and tanks, provide large-scale storage for harvested rainwater allowing controlled release of water during dry periods, ensuring a steady supply for irrigation and reducing the risk of drought. The combined application of ASSM and RWH will boost agricultural produce and mitigate against flooding. As water availability increased, RWH and ASSM provided a reliable source of water for irrigation [115], allowing farmers to grow more crops and increase yields. This will improve soil health by replenishing groundwater, improving soil moisture and reducing soil salinity. It can also enhance nutrient availability by delivering nutrients to crops and optimizing plant growth. On the other hand, RWH captures rainwater, reducing the volume of water flowing into rivers and streams, mitigating flood risks, while controlling the release of stored water, preventing sudden surges and reducing flood damage. The implementation of RWH and ASSM will improve water security, boosting agricultural production and safeguarding communities from the devastating effects of flooding. However, while this study provides compelling case for ASSM and RWH as sustainable water solutions, it is methodologically limited in terms of how sources have been chosen and evaluated. The review is predominantly qualitative in form with little critical comparison between geographical or technological context. Empirical verification is merely secondary data dependence with no field measurements. Furthermore, socio-political and economic feasibility studies remain inadequately researched, and environmental hazards of large-scale infrastructure are insufficiently explored. These deficiencies can be filled in with systematic analysis of data, stakeholder views, and impact modeling, enhancing the study's appropriateness and policy relevance.

6 Recommendation and the way forward

Going forward, it is important to know that one of the primary water challenges facing many regions of the world today is water scarcity. According to the United Nations, over 2 billion people live in countries experiencing high water stress, and this number is expected to increase as water demand continues to rise [116]. Water scarcity not only affects human populations but also has significant implications for agriculture, industry, and ecosystems. In addition to scarcity, water quality is also a major concern, with pollution from industrial, agricultural, and urban sources leading to health risks and environmental degradation [117–119]. To address these challenges, it is essential to adopt a strategic approach to water resource management that takes into account the complex interplay of social, economic, and environmental factors. Traditional geophysical approaches to water management, such as building dams, reservoirs, and irrigation systems, have been important in meeting water demand. However, these approaches often have significant environmental and social impacts, and their effectiveness can be limited by factors such as climate variability and changing land use patterns. In this context, exploring alternative solutions such as RWH and AASM can offer a more sustainable and decentralized approach to water resource management. RWH and AASM involve capturing and storing rainwater for later use, reducing reliance on centralized water supply systems, and alleviating pressure on natural water sources. This approach has the potential to provide a reliable and cost-effective water supply for domestic, agricultural, and industrial use, particularly in regions where traditional water sources are scarce or unreliable.

Furthermore, RWH and ASSM can contribute to sustainable development by promoting water conservation, reducing energy consumption, and enhancing resilience to climate change. Communities can lessen their dependency on surface and groundwater supplies by collecting rainfall, helping to alleviate pressure on aquifers and rivers. This can also help to mitigate the impacts of drought and water scarcity, as stored rainwater can be used during dry periods to maintain essential water services. In addition to its direct benefits for water supply, RWH can also have positive environmental and social impacts. By reducing the demand for centralized water supply infrastructure, RWH can help conserve natural ecosystems and reduce the energy and carbon footprint associated with water treatment and distribution. Furthermore, decentralized RWH systems can empower communities to take control of their water supply, promoting local resilience and self-sufficiency. However, realizing the potential of RWH requires a strategic and integrated approach that takes into account local conditions, social dynamics, and institutional frameworks. This includes addressing technical, financial, and regulatory barriers to the adoption of RWH, as well as promoting awareness and capacity building among stakeholders. Furthermore, it is essential to consider the potential trade-offs and synergies between RWH and other water management strategies, such as water conservation, water reuse, and ecosystem-based approaches.

It is a basic human need and right to have access to clean water, proper sanitation, and hygiene practices for overall health and well-being. Nonetheless, projections indicate that in 2020, almost 2 billion people will lack access to clean drinking water. According to the report, more than 40% of the world's water bodies do not meet quality criteria, and in many regions of the world, water pressure has climbed above 70% [120]. The report also recommends that the international community increase its assistance

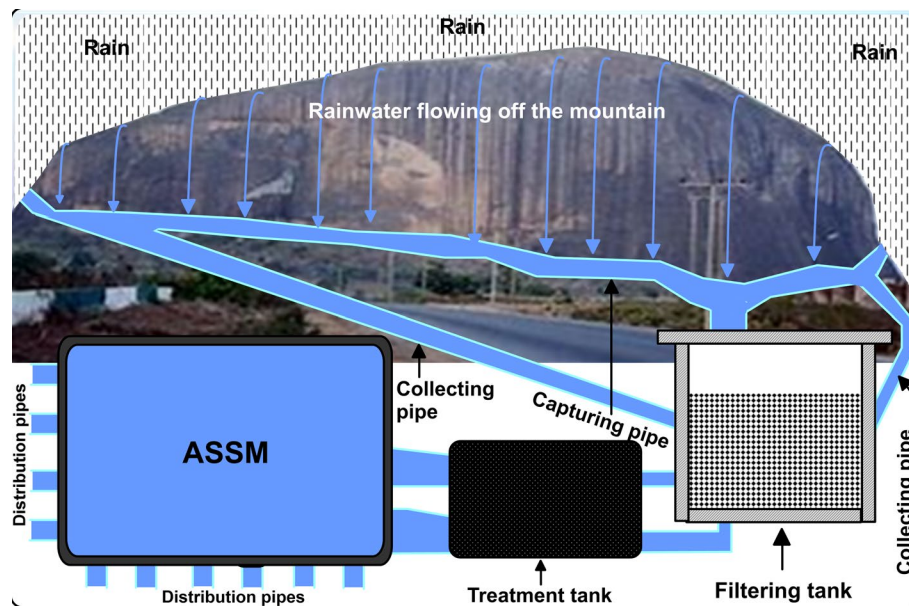


Fig. 6 A RWH and ASSM Systems Using a Natural Rock for Capturing Rainwater

to developing countries to generate more funding for local communities and ground-water development in the area. In addition, ASSM and RWH can contribute to flood control by capturing excess water during periods of snowmelt or heavy downfall [105, 121], and ASSM can release it during dry seasons when water availability is highly limited to ensure steady water running for different usages such as industrial, agricultural, and domestic needs, which will be minimizing the dependence on unpredictable weather patterns [26]. This helps preserve the integrity of ecosystems and habitats that depend on steady water levels in addition to ensuring human survival and well-being. If the method is allowed by state and/or municipal regulations, RWH is a great way to add water for on-site use. When used properly, rainwater reduces the amount of potable water used. Instead of letting precipitation run, evaporate, or seep into the earth, RWH covers procedures that redirect, capture, and store precipitation for use on-site. The captured precipitation may need to be treated depending on how it will be used. RWH can, in general, also refer to collection from surface water runoff; however, runoff is governed by surface water rules in the United States [122].

In addition, future research should also deploy hydrological modeling, such as (e.g., SWAT and MODFLOW) to simulate the impacts of ASSM and RWH on flood mitigation and aquifer recharge. For instance, a longitudinal field study with water quality monitoring and GIS-based spatial analysis can assess environmental outcomes, while the cost-benefit and socio-economic impact assessment tools, such as multi-criteria decision or Probit models analysis, are vital for adoption feasibility. Additionally, climate-resilient scenario modeling should be integrated to evaluate performance under extreme weather conditions. These approaches will strengthen empirical validation and guide scalable implementation.

To continue exploring new technologies and strategies for ASSM and RWH, ensuring their effectiveness and scalability. For instance, the utilization of mountains as in Fig. 6, to collect rainwater can be a perfect example effective method of RWH to harness natural resources and ensure a sustainable water supply. For sustainable water management,

utilizing natural catchment areas such as mountains (Fig. 6) to collect rainwater is critical. These areas can capture large volumes of rainwater that would otherwise run off quickly [115]. Implementing storage systems like reservoirs, tanks, or natural mountains at higher elevations to store the collected rainwater can help regulate water flow and provide a steady supply during dry periods [72]. This is because it uses gravity-fed channels or pipes to transport rainwater from the catchment areas to storage systems or directly to areas where it is needed. This technique alone cannot guarantee a quality water supply. Therefore, the need to install filter systems to shield the contaminants and debris from the collected rainwater, ensuring it is safe for use is critical. It also creates recharge zones where rainwater can percolate into the ground, replenishing groundwater aquifers and maintaining the water table [41], providing a reliable source of water for agricultural irrigation, industries, and other uses. Additionally, it also reduces the risk of flash floods by capturing and storing excess rainwater, promotes groundwater recharge and maintains ecological balance.

Therefore, educating communities about the benefits of these approaches is crucial for their adoption. These approaches should be considered as essential components of sustainable city development, ensuring water security for future generations. The water crisis is a complex challenge, but it's not insurmountable. By embracing innovative solutions like ASSM and RWH, we can secure a future where everyone has access to clean and safe water. In conclusion, RWH technology is becoming more and more popular when it comes to sustainability and water security. In the future, RWH technology ought to be included in the building's architecture as a means of collecting rainwater, which might then be directed into subterranean cisterns for irrigation and other relevant water uses. To assist future water managers in putting their good intentions into action, this study examines the evidence about various forms of water storage and speculates on what a new, integrated storage agenda for the twenty-first century might include.

7 Conclusion

The world is facing a water crisis, with a projected 40% decrease in available water supply by 2030. Over 40% of the global population already experiences water scarcity, a reality underscored by the staggering decline in natural freshwater storage, a loss of 15,700 BCM between 1970 and 2019. Traditional water management approaches are simply not enough. This paper presents a compelling case for embracing Additional Storage Support Mechanisms (ASSM) and Rainwater Harvesting (RWH). Real-world examples demonstrate their potential: a single RWH structure in India stored 12,000 m³ of water, while rainwater infiltration through a shallow well in Hungary yielded 60.616 m³. These numbers highlight the effectiveness and scalability of these approaches. ASSM and RWH offer a decentralized approach to water management, empowering communities and reducing reliance on centralized systems. They represent a more sustainable and cost-effective way to manage water resources, offering a path towards a future where everyone has access to clean and safe water. The time to act is now. Let's invest in research, promote awareness, and integrate these innovative solutions into our urban planning. The future of water security depends on it.

Author contributions

JOA conceived, designed, and wrote the manuscript, and all other authors (SUE, GIO, AAI, DAA, OJO, FA, MA, and DOA), including JOA are involved in Investigation, Data Acquisition, Data processing, Analysis, and Resources, reviewed the manuscript.

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Data availability

All the materials and data used for this research are available and online in published works, and all requests should be addressed to the corresponding author (JOA) and co-author

Declarations**Declarations****Ethical approval.**

This study adhered to established ethical standards and guidelines. No human or animal subjects were involved, and all referenced data sources were properly acknowledged.

Consent to Participate

All contributing authors provided informed consent to participate in the development and review of this manuscript.

Consent to Publish

All authors have reviewed and approved the final version of the manuscript and consent to its publication for academic and scientific purposes.

Competing Interests

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