Sustainable Approaches for Optimizing Potable Water Supply

Edward Shakes

Central Global University

Professional Doctorate (VAE) Program

SID: CGUPDVAE2421

Date: November 6, 2025

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Introduction

Water is essential for sustaining life on Earth. Water is an indispensable resource for humanity, meeting the needs of hydration, sanitation, energy, industry, and transportation. Freshwater is the primary form of water used for domestic and industrial purposes. However, the supply is limited when compared to the vast proportion of the planet's water. Approximately 1% of the Earth's surface water is available as fresh drinking water (Choubey et al., 2022). The Earth's freshwater supply is also threatened by climate change, which can alter hydrological cycles and cause extreme weather events, such as droughts and flooding (Melaku Melese, 2016; Retter et al., 2020). In recognizing the risks and limitations that affect potable supply, the need exists for effective and efficient engineering and management systems to secure this valuable resource. Therefore, actions should be taken to limit waste, optimize water consumption, and reuse wastewater. This journal explores three sustainable approaches for the design and management of potable water: pressure control and water loss reduction management, rainwater harvesting, and greywater reuse.

Water Supply Sustainability in Context

Maintaining an adequate and efficient water supply is essential for a nation's development. Sustainable water management is essential for human health, economic development, and environmental conservation purposes. This requires a multifaceted approach that includes water conservation, supply augmentation, improved distribution, and the treatment of contaminants (Alexandratos et al., 2019). As urban areas continue to expand, the complexity of managing water-supply systems intensifies. This increase in demand is driven by urbanization, climate change, and varying consumer needs. Moreover, the issue of water scarcity, particularly in arid and semi-arid regions, underscores the need for adaptive management strategies. Sustainable practices must consider both the temporal and spatial aspects of water supply availability and demand. For grid water supply systems, emphasis should be placed on reducing water volume losses from leaks and theft, reducing electrical energy consumption for pumping systems, and maintaining optimized abstraction volumes from supply sources such as rivers, lakes, streams, and wells. A pressure control and water loss reduction project in the Bahamas reduced leaks from 60% to 30% of the total water supplied to the country, with cost savings of 10 million USD per year (World Bank , 2025). Rainwater harvesting is an effective alternative if a grid water supply network is inaccessible, expensive, or unreliable. In Dhaka, Bangladesh, rainwater harvesting projects were successfully implemented to supply over 20 percent of the water demand for the unreliable potable supply network (Karim et al., 2021). Recycling greywater can reduce the consumption of treated potable water for irrigation and sanitation. This was demonstrated in Tufileh, Jordan, from a project where greywater was reused in home gardens, which reduced potable water bills by 27% (Faruqui & Al-Jayyousi, 2002).

Optimizing existing water supply networks through pressure control and water loss reduction; rainwater harvesting; and greywater reuse will sustain water supply systems by improving potable water use, reducing operational costs, using cheaper water supply alternatives, and improving water conservation. The degree of application or utilization of these approaches depends on capital costs, revenue potential, and the cost recovery period. Therefore, projects and system designs must be scaled towards the intended benefits of the implementing organization or system owners. Overall, these sustainability strategies collectively contribute to the long-term resilience and sustainability of water supply systems, ensuring reliable access to this vital resource amid growing demand and environmental challenges.

Pressure Control and Water Loss Reduction Management

Pressure Control and Water Loss Reduction Overview

Pressure control and water loss reduction management in potable water supply networks is critical for maintaining the efficiency and sustainability of water distribution. Several strategies and methods have been proposed to address this issue.

A prominent strategy is pressure management, which is crucial for reducing water loss through leakages in the water distribution networks. By controlling the pressure in the system, the leakage flow rate can be reduced, and the likelihood of pipe bursts or cracks can be minimized. Pressure management strategies are essential for reducing leakage and saving energy resources

(Adedeji et al., 2018). Hydraulic modeling combined with pressure control has been shown to significantly reduce leakages. For instance, lowering the pressure from 51 m (5 bar) to 20 m (2 bar) in a district-metered zone resulted in a 10% reduction in leakage (Alsaydalani, 2024).

Additionally, the integration of technological innovations, such as Geographic Information System (GIS) monitoring systems and the use of advanced detection devices (geophones, stethophones, and correlators), enables the quick detection and localization of leaks (Ociepa et al., 2019). Continuous monitoring using these systems enables real-time assessment and implementation of corrective actions, thereby significantly reducing water loss.

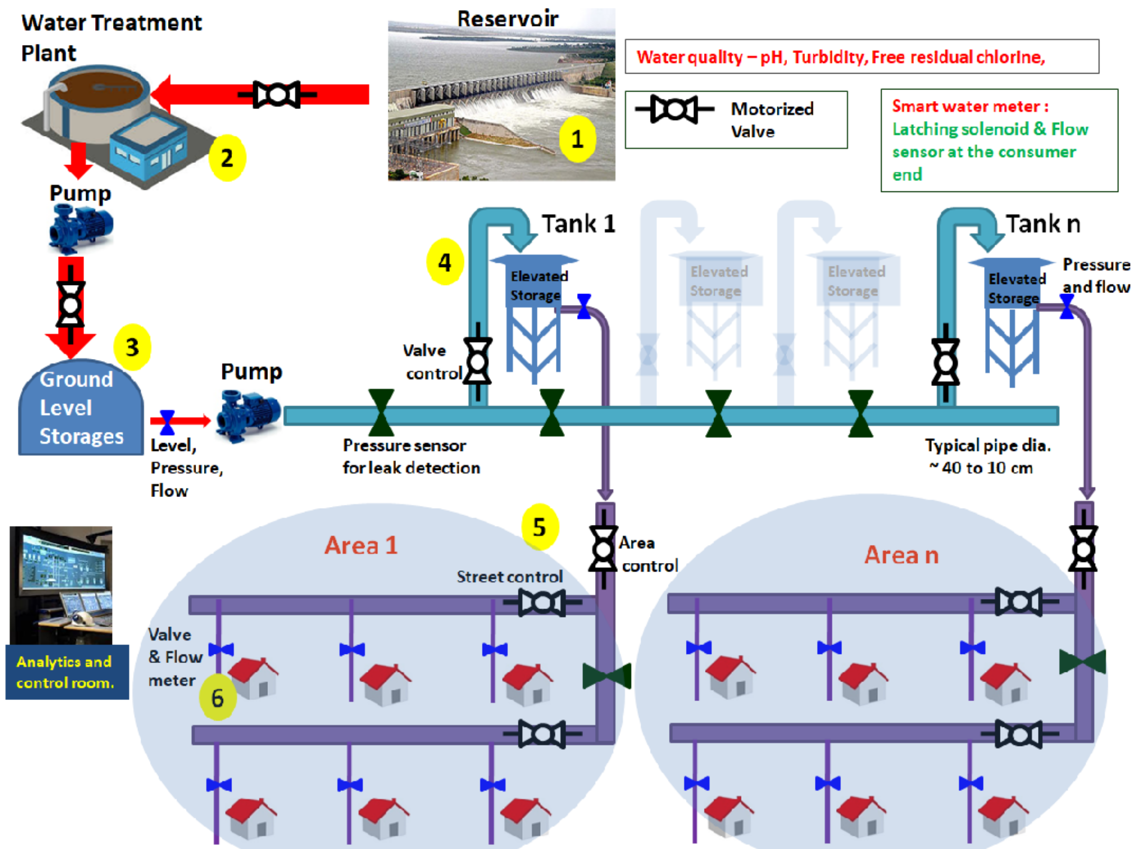
District metering is an effective method for reducing leakage. It involves monitoring the water flow and pressure in specific sectors of the network, allowing targeted maintenance and management (Ahopelto & Vahala, 2020). Similarly, the use of Artificial Neural Networks (ANN) for estimating leakage ratios, as demonstrated in a study using Principal Component Analysis (PCA) integrated with ANN, offers accurate leakage estimations and helps in decision-making for sustainable management (Jang et al., 2018).

Comprehensive initiatives and regular assessments have proven successful in reducing water losses in selected water supply systems, achieving a substantial decline in the non-revenue water (NRW) index (Ociepa et al., 2019). Such efforts include pipe replacement, upgrading old infrastructure, and implementing more accurate water metering technologies, among others.

Overall, the combination of pressure management, technological advances in leak detection, and strategic infrastructure maintenance form the cornerstone of effective water-loss management in potable water supply networks. These approaches not only enhance resource efficiency but also substantially reduce the costs associated with water losses. A layout of an optimized smart water distribution network is shown in figure 1 below:

Figure 1

Layout of a smart water supply city network



Note. Schematic layout of a water distribution network with smart control systems to monitor system performance with leak detection equipment, pressure sensors and control valves (Mohanasundaram, et al., 2018)

Approach for Pressure Control and Water Loss Management

The following steps are needed for the design and management of optimizing and reducing losses in existing potable grid water supply systems.

- **Perform a Water Balance on the Network**
  - The daily volume of water input from sources such as treatment plants and wells must be measured.
  - Measure the water consumption of customers connected to the supply network.
  - Calculate system losses by subtracting total consumption from total supply volume.

    - If losses exceed 50% of the consumption volume, they are considered significant and require further investigation.
- **Conduct a Water Supply Network Audit and Project Planning**
    - Survey and inspect the network infrastructure to identify system pressures, flow rates, leaks, illegal connections, and operational inefficiencies.
    - Technological tools, such as geographic information system (GIS) monitoring systems, geophones, stethophones, and correlators, are used for accurate leak detection and localization.
    - Hydraulic modelling is performed to simulate the existing system pressures and flows to determine the pressure management approach, district metering zones, and system infrastructure upgrades.
    - Define the project scope, schedule implementation activities, and determine the project cost.
    - Assess the economic viability of the project by determining project revenue, operation costs, cost savings, project payback period, and internal rate of return. If required, adjust the project scope, activity schedule, and costs to make the project more viable.
    - Finalize the project scope, schedule, and cost based on economic viability.
- **Implement Pressure Management**
    - The pressure within the network should be controlled and optimized to reduce leakage flow rates and prevent pipe bursts or cracks from occurring.
    - Hydraulic modeling was used to simulate and adjust the pressure zones effectively, as demonstrated by the reduction in leakage with pressure adjustments. The pressure at consumer connections should be between 14 m (1.4 bar) and 49 m (4.9 bars).
- **District Metering Zones (DMZs) Establishment and Leak Repairs**
    - The network is divided into sectors with dedicated metering and pressure monitoring to detect and isolate leaks.
    - Repairing detected leaks, disconnecting illegal or unauthorized water connections, and installing pressure control devices to maintain system pressure and prevent future leaks.
- **System Infrastrure Upgrades (If required)**
    - Replace aging or damaged pipes to reduce leaks.

- Install accurate water metering technologies to improve consumption tracking and reduce non-revenue water (NRW).
- If necessary, solar photovoltaic systems, energy-efficient pumps, and storage tanks should be installed to reduce electrical energy consumption.

- **Sustainable System Management and Operations**
  - Minimize water theft and unauthorized use through monitoring and enforcement strategies.
  - The electrical energy consumption for pumping can be reduced by optimizing the abstraction volumes and pump operation schedules.
  - Hydraulic system loggers were installed to monitor water supply network flow volumes, system pressure, and leaks.
  - Develop a preventative maintenance plan to ensure that water supply network operations are efficient and effective.
  - Implement corrective actions to ensure optimum system operations.
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Rainwater Harvesting

Rainwater Harvesting Overview

Rainwater harvesting is the process of collecting and storing rainwater from surfaces such as rooftops, land surfaces, and rock catchments for future use. It serves as an effective alternative or supplement to the grid water supply, particularly in areas where the conventional water supply network is inaccessible, expensive, or unreliable. The fundamental aspects of rainwater harvesting are as follows:

Collection: Rainwater is captured from catchment areas, commonly roofs, and directed through gutters and downspouts into storage containers or recharging systems for collection.

Storage: Collected rainwater is stored in tanks, cisterns, and reservoirs for future use. Proper storage design is essential for minimizing contamination and evaporation losses.

Utilization: Harvested rainwater can be used for various purposes, such as potable water supply (after appropriate treatment), irrigation, sanitation, and industrial use.

Designing a rainwater harvesting system involves careful consideration of various factors, such as the sizing of storage tanks, catchment areas, and local climate conditions. Optimal system sizing is crucial to ensure reliability and minimize costs without compromising water quality or system performance. A poorly sized system could be insufficient or lead to higher costs and potential risks (Semaan et al., 2020).

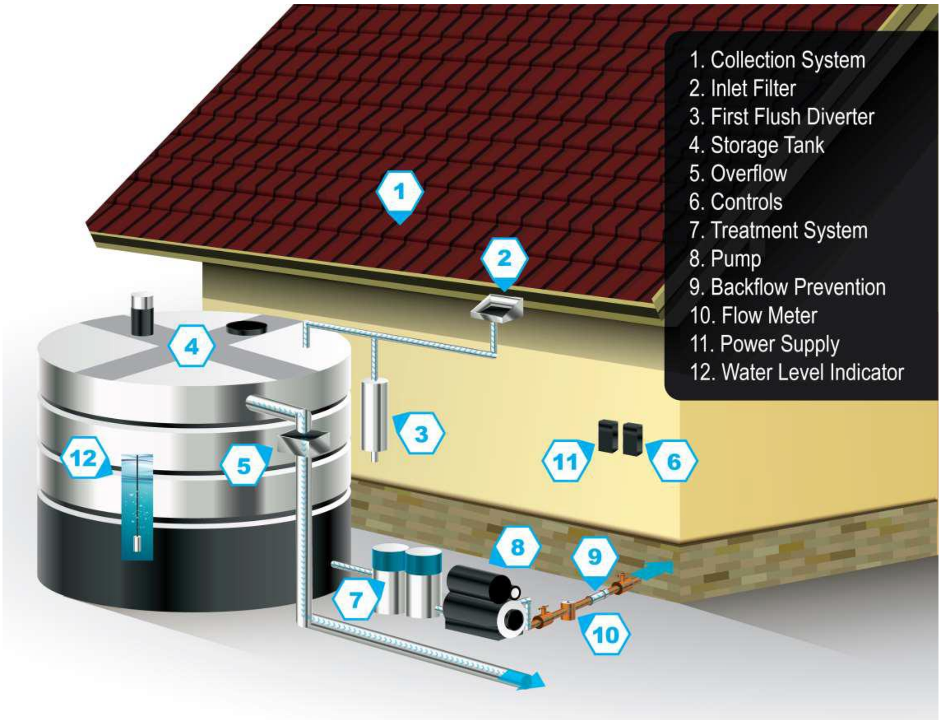
Rainwater harvesting systems serve as an alternative water supply and play a role in stormwater management. Innovative technologies, such as active and passive release systems, have been developed to enhance the dual functionality of these systems by balancing water conservation with stormwater control. This is particularly significant in non-arid regions, where systems tend to remain full, limiting their capacity to manage stormwater effectively (Gee & Hunt, 2016).

Moreover, these systems are influenced by regional climate, which affects their design and performance. For instance, the different climatic regimes in Italy require tailored designs that consider the intra-annual variability in rainfall to optimize the volumetric retention and runoff mitigation capabilities of the system (Campisano et al., 2013).

Overall, rainwater harvesting systems contribute to the sustainability of urban environment. They reduce dependence on centralized water supplies and mitigate the impact of urban stormwater runoff, making them a valuable addition to city infrastructure planning (Quinn et al., 2020; Teston et al., 2022). A diagram of a typical rainwater harvesting system is shown in figure 2.

Figure 2

A Greywater Harvesting System with Typical Components



Note. Layout of a typical rainwater harvesting system with collection, conveyance, storage, filtration and treatment equipment (Stephens, 2019)

Rainwater Harvesting System Design and Management approach

Rainwater harvesting system installation and management involves the following key components and practices:

- **System Design and Planning**
    - Determine the rainfall quantity at the proposed installation site in mm or inches from credible meteorological data sources. Calculate the rainwater collection or catchment area. The rainfall quantity must be multiplied by the catchment area to obtain the expected rainwater volume flow.
    - Estimate the water supply demand volume flow at the location. If the demand flow is larger than the rainwater volume flow, additional potable water sources are required for continuous operation. If the demand is lower than, an additional

source may not be necessary or can be used as a backup supply for system maintenance.

- Determine the tank storage volume. The tank storage volume must be greater than or equal to the estimated rainwater volume to avoid overflow.
- Pumps should be sized to meet or exceed the water supply demand flow and pressures between 14 m (1.4 bar) and 49 m (4.9 bar).
- First-flush systems, filters, piping, and additional equipment specifications should be determined in consultation with suppliers and experts.
- Determine the scope and cost of installing a rainwater harvesting system.
- The economic viability of the project was determined by comparing the operational costs and cost savings when compared with using a grid potable water supply network with the installation cost of the rainwater harvesting system. If required, adjust the scope and cost to make the project viable.
- Finalize the project scope, cost, and activities.

- **System Installation**
  - **Collection:** Install gutters and downspouts to capture rainwater from roofs or catchment surfaces. Filters are installed at gutters to remove debris, including leaves and sediments. First-flush diverters should be installed at the bottom of the downspouts to remove highly contaminated rainwater from the gutters during cleaning and maintenance.
  - **Storage and water treatment:** Install storage tanks, cisterns, or reservoirs. A treatment system should be installed to make the water suitable for consumption. Ultraviolet (UV) or chlorination systems can be installed for the disinfection of water, and additional filters can be installed for removing fine particles.
  - **Water Conveyance:** Install piping and pumping systems that are appropriately sized for the rainwater volume and demand volume flow. The pipe sizes typically range from 25 mm to 250 mm in diameter.
  - **System Control Devices:** Overflow, control, and backflow prevention devices should be installed to optimize operations while preventing wastage and system failure.

- **Utilization:** Harvested rainwater is used for potable supply (after treatment), irrigation, sanitation, or industrial purposes.

- **Sustainable System Management and Operations**
  - Regular maintenance and monitoring of storage tanks and collection components are required to prevent contamination and system failures.
  - Integration with existing water supply systems to supplement unreliable or expensive grid supplies.
  - Regional climate impacts should be considered when tailoring system design and operation for maximum efficiency.
  - Combining rainwater harvesting with other water conservation strategies, such as graywater reuse and loss reduction in supply networks, is recommended.
  - Monitoring tools, such as hydraulic system loggers, are used to oversee flow volumes, pressures, and leak detection in broader water supply networks.
  - Implement preventive maintenance plans and corrective actions to ensure efficient and effective system operation.
  - Employ energy-efficient equipment (e.g., pumps and solar photovoltaic systems) to reduce electrical consumption related to water supply and storage.

Greywater Reuse

Greywater Reuse Overview

Greywater reuse involves the collection and recycling of lightly used water generated from domestic activities, such as bathing, laundry, and handwashing. This water, which typically contains fewer contaminants than blackwater (sewage), is treated to an appropriate level and repurposed for non-potable applications, including irrigation, toilet flushing, and sanitation purposes. By diverting greywater away from conventional wastewater streams and reducing the reliance on treated potable water, greywater reuse contributes significantly to conserving freshwater resources and lowering the operational costs associated with water treatment and water supply.

In practical terms, greywater is collected at the household or community level from specific sources such as bathroom sinks, showers, and washing machines. It undergoes treatment processes that may include filtration, sedimentation, biological treatment, and disinfection to remove physical, chemical, and microbial contaminants to levels that are safe for the intended reuse applications. The treated greywater is then redirected for uses such as watering in-home gardens, landscaping, or flushing toilets, thereby reducing the volume of potable water consumed for these purposes.

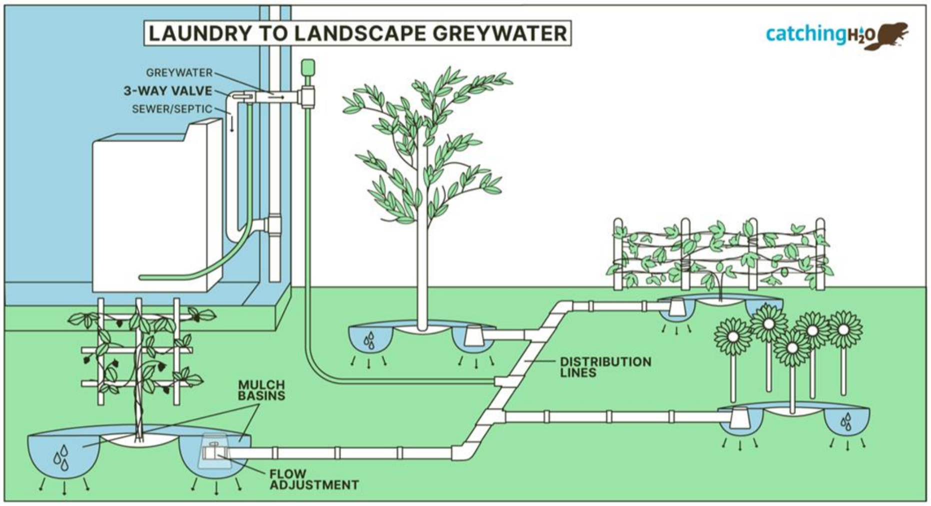
Designing and managing greywater systems involves several key considerations to ensure their effective operation and sustainability.

Greywater should be collected separately from blackwater (toilet water) as it generally contains lower levels of pathogens and is easier to treat for reuse in non-potable applications (Khajvand et al., 2022). The systems should be scalable and space-efficient, particularly in urban environments, where space is limited. Combining greywater systems with rainwater harvesting can enhance water conservation and supply efficiency, as demonstrated in studies of households with high water consumption (Gómez-Monsalve et al., 2022). A comprehensive evaluation of the environmental performance of greywater systems is crucial, including the potential for energy recovery and reduced pollutant discharge (Ghaitidak & Yadav, 2013; Kordana-Obuch et al., 2023).

Regular maintenance of greywater systems is critical to ensure optimal performance and longevity of the systems. This involves routine checks, servicing of mechanical components, and periodic harvesting of plants in phytoremediation systems (Prasad et al., 2021). Monitoring the quality of treated greywater to ensure that it meets safety standards for its intended reuse, such as irrigation and toilet flushing, is essential (Oteng-Peprah et al., 2018).Public perception significantly impacts the success of greywater reuse systems. Ensuring transparency in treatment processes and maintaining high safety standards can improve user acceptance (Oteng-Peprah et al., 2018). A typical layout of a simple greywater reuse system is shown in figure 3 below.

Figure 3

Laundry to Landscape Greywater Reuse System



Note. Simple Laundry to Landscape greywater reuse system with greywater conveyed from a washing machine to plants and trees for irrigation (Catching H20, 2025)

Greywater Reuse Design and Management Approach

To design and manage a greywater reuse system, the following must be done:

- **System Design and Planning**
    - Determine the proposed site for the system installation and intended use, whether for irrigation, sanitation, or toilet flushing.
    - Determine the required flow from th greywater source. Flow should range from 6 cubic meter per day per hectare to 33 cubic meters per day per hectare.
    - Examine existing flow rates from the greywater sources to check if they are in the range of the required flow or greater.
    - Advanced toilet flushing and sanitation systems require a treatment system. For irrigation purposes, less treatment of greywater is required, especially for laundry-to-landscape systems.
    - Determine the scope and cost of installing a greywater reuse system.
    - Determine the economic viability of the project by comparing the operational costs and cost savings when compared with using a grid potable water supply network with the

installation cost of the rainwater harvesting system. If required, adjust the scope and cost to make the project viable.

- Finalize the project scope, cost, and activities.

- **System Installation**
  - Greywater should be collected from domestic sources, such as bathroom sinks, showers, and washing machines.
  - Treatment components must be installed for toilet flushing and sanitation. These may include sedimentation vessels, filters, and UV or chlorination disinfection systems to reduce physical, chemical, and microbial contaminants to safe levels for intended reuse.
  - For irrigation of landscapes and gardens, mulches basins can be installed in the gardens or plant area to filter sediments and small particles from grey water.
  - Install piping equipment, preferably made of plastic, with diameters no less than 25 mm and 3-way valves to direct greywater to the intended use, and when not in use, a bypass to the sewerage conveyance.
  - If necessary, pumps may be installed to transmit treated greywater to locations that require higher pressures.

- **Sustainable System Management and Operations**
  - Rainwater harvesting should be combined with other water conservation strategies, such as greywater reuse and loss reduction in supply networks.
  - Continuous monitoring of treated greywater quality is required to ensure compliance with the safety standards for reuse.
  - Implement preventative maintenance plans and corrective actions to ensure efficient and effective system operation.
  - Employ energy-efficient equipment (e.g., pumps and solar photovoltaic systems) to reduce the electrical consumption related to water supply and storage.

Conclusion

This journal provides a comprehensive overview of sustainable water supply management, emphasizing the need to optimize water resources amid growing demand and environmental challenges. It covers key strategies such as pressure control and water loss reduction in potable supply networks, rainwater harvesting, and greywater reuse, all of which enhance water conservation and operational efficiency.

Effective pressure control and water loss management employs pressure control, advanced leak detection, district metering, and infrastructure upgrades to reduce non-revenue water and its associated costs. Rainwater harvesting offers a reliable alternative or supplement to grid supply, especially in areas where networks are unreliable or inaccessible, and supports stormwater management and urban sustainability. Proper design, installation, and maintenance ensure system reliability.

Greywater reuse reduces potable water consumption for non-potable uses such as irrigation and sanitation. Successful implementation requires separate collection, appropriate treatment, system scalability, and public acceptance.

Together, these integrated approaches optimize resource use, lower operational costs, and improve resilience, thereby supporting sustainable water supply systems vital for socioeconomic development and environmental conservation.

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