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A framework for designing a water quality monitoring plan for decentralized rainwater harvesting drinking water supply systems: a case study in the Netherlands

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ABSTRACT

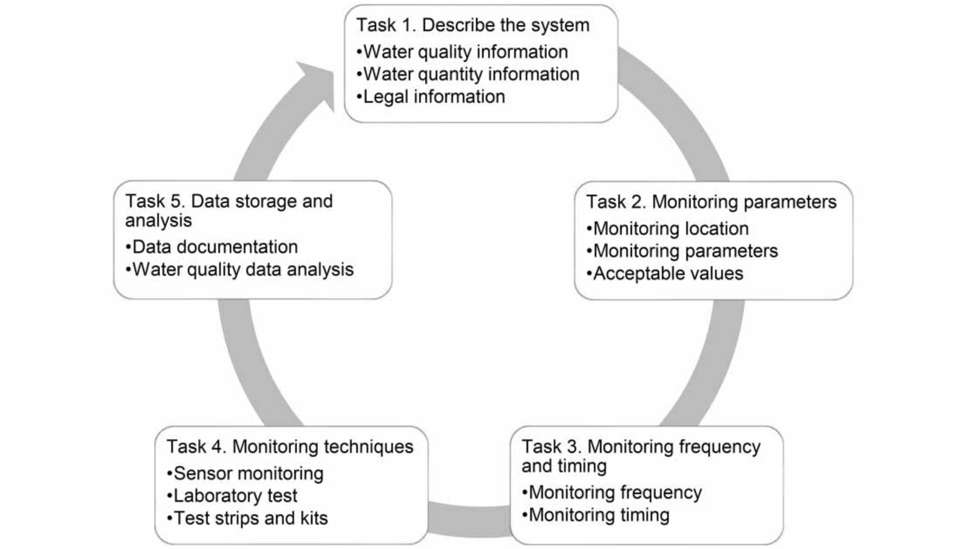
Rainwater harvesting (RWH) is increasingly adopted as a decentralized water source, yet there are no regulations or policies ensuring its safety for drinking purposes. This paper introduces a five-step iterative framework to build a water quality monitoring plan for such systems comprising system description, monitoring parameters, monitoring frequency and timing, monitoring techniques, and data storage and analysis. To illustrate its practical application, the framework is applied to Superlocal, a community scale rainwater harvesting project in Kerkrade, the Netherlands, where rainwater is collected and treated locally to supply drinking water. Applying this framework, the manuscript provides detailed implementation guidance. In the absence of specific RWH regulations, the study adapts existing Dutch drinking water regulations (DWB and DWR) and utilizes a historical rainwater quality database to inform parameter selection, thresholds, and monitoring frequencies. The analysis reveals that water production and monitoring costs for Superlocal total €4.60/m^3, considerably higher than for centralized systems in the Netherlands. As decentralized RWH systems are increasingly integrated into climate adaptation strategies for urban water, this work highlights barriers and enablers for advancing safe and sustainable decentralized water management. The study recommends policy interventions and cooperative management models to enhance the economic viability and safety of these systems.

Key words: Decentralized drinking water systems, Drinking water quality guidelines, Rainwater harvesting, Water quality assurance regulation, Water quality monitoring plan

HIGHLIGHTS

- A framework is proposed for designing water quality monitoring plans for decentralized rainwater harvesting systems for potable use.
- A real community-scale RWH system in the Netherlands is used to showcase how appropriate monitoring parameters, techniques, and frequencies should be considered based on existing Dutch regulations and a historical rainwater quality database.
- Policy recommendations made to improve (economic) feasibility of RWH systems.

GRAPHICAL ABSTRACT



Framework tasks for RWH drinking water monitoring: a continuous assessment and update cycle

1. INTRODUCTION

Rainwater harvesting (RWH), which dates back 2,500 years (AbdelKhaleq & Ahmed 2007), is currently receiving increasing attention as a supplementary resource in decentralized water supply for watering gardens, livestock, irrigation, and domestic use with proper treatment (Alim *et al.* 2020a,b; Sakati *et al.* 2023). Shefaei *et al.* (2025) and the multiple references therein document the large number of recent literature dealing with the design and optimization of these systems. Research also shows the growing role of RWH in supplementing drinking water in many rural and urban communities around the world (Gispert *et al.* 2018; Alim *et al.* 2020a,b, 2021). RWH is being used in countries all over the world, among which Japan, Thailand, Australia, Germany, and the United States have extensive RWH system development (Campisano *et al.* 2017).

Three drivers can be distinguished as responsible for the growth in attention to RWH. Firstly, through the collection and storage of rainwater, rather than allowing it to run off roofs and other paved surfaces, it can have additional benefits in reducing the risk of flooding in urban areas (Jamali *et al.* 2020). Climate change is intensifying extreme rainfall events and is projected to increase their frequency and intensity in Western Europe (van den Hurk *et al.* 2006; Intergovernmental Panel on Climate Change (IPCC) 2023). Existing urban drainage systems cannot deal with these extreme events and to prevent pluvial flooding, increasing storage capacity for rainwater in tanks or aquifers can be a potential solution (Hofman-Caris *et al.* 2019). Secondly, RWH is gaining increasing attention as a measure to mitigate water scarcity. Climate change is expected to alter both the quantity and temporal availability of freshwater resources, potentially leading to shortages in many regions (Wu *et al.* 2020). At the same time, population growth, higher living standards, and expanding industrial activity continue to raise overall water demand. Although household and industrial water-use efficiencies in the Netherlands have historically been improving, total demand is still projected to increase due to population and urban growth. Within this context, collecting and storing rainwater in urban areas provides a valuable supplementary source that can reduce pressure on existing centralized supplies (Aladenola & Adeboye 2009). As an example, the Dutch National

Institute of Public Health and the Environment (RIVM) published a report outlining the possibility at present that surface and groundwater sources will be insufficient to meet the drinking water demand in 2030, and the use of rainwater is suggested as one of the adaptation strategies to address emerging drinking water shortages (van Leerdam *et al.* 2023).

Thirdly, water utilities observe a social trend of an increasing number of people adopting a more sustainable lifestyle and showing a willingness to make personal efforts to reduce their ecological footprint (Hofman-Caris *et al.* 2019). RWH is considered a measure that could significantly contribute to a more sustainable lifestyle. As a result, drinking water utilities are increasingly confronted with customers wishing to live 'off-grid', and to use rainwater for the decentralized production of drinking water. The decentralized RWH water supply system considered in this paper is a community-scale system that collects, treats, and distributes rainwater locally through a small treatment facility.

Harvested rainwater can be used for potable applications and non-potable applications, such as drinking, toilet flushing, washing machines, and garden watering. For both potable and non-potable applications, health risk assessments and quality assessments have been performed. Kusumawardhana *et al.* (2021) studied the microbial health risks arising from the implementation of RWH for household use, especially for toilet flushing. The results showed that using rainwater without prior treatment poses an annual infection risk which exceeded the Dutch drinking water standard of 10^{-4} pppy (1 infection per 10,000 persons per year). The study of Schets *et al.* (2009) showed that roof-collected rainwater stored in reservoirs is frequently fecally contaminated and incidentally contains potential human pathogens such as Campylobacter, Cryptosporidium, Giardia, Aeromonas hydrophila, and Legionella. These studies suggest that harvested rainwater does not meet potable water quality standards and, therefore, water treatment is necessary before using rainwater as drinking water.

Given these treatment requirements, the water quality regulatory framework for RWH applications becomes critical. With respect to regulations and laws concerning the application of RWH, several countries have established rules for its use, particularly for non-potable purposes (GhaffarianHoseini *et al.* 2016; Campisano *et al.* 2017; Hamilton *et al.* 2017). For example, in Germany, due to strict drinking water standards and severe industrial air pollution, rainwater collected by households can only be used by industry for non-potable purposes. However, clear regulations governing the use of harvested rainwater for drinking water supply remain absent at both the EU and national levels. The European Drinking Water Directive (DWD) (European Parliament, Council of the European Union 2020) for example provides quality standards for drinking water regardless of its origin, yet it does not explicitly address rainwater as a potential source. This regulatory gap highlights the need for guidance on how to apply existing drinking water quality frameworks to decentralized RWH systems intended for potable use.

As the main law on drinking water quality, the EU's DWD (European Parliament, Council of the European Union 2020) concerns the access to and the quality of water intended for human consumption to protect human health. It gives standards for drinking water regardless of its origin. As such, it gives quality standards for the harvested rainwater after treatment. The EU DWD applies a risk-based approach and requires a risk assessment and risk management of the catchment areas for abstraction points of water intended for human consumption, as described in Article 8 of the DWD. Risk assessment and risk management of abstraction point catchments should take a holistic approach and aim to reduce the level of treatment required to produce water for human consumption, for example, by reducing the pressure to pollute, or the risk of polluting. To that end, Member States should characterize the catchment areas of abstraction points and identify hazards and hazardous events that could cause the quality of the water to deteriorate, such as possible pollution sources associated with those catchment areas. The catchment areas refer to groundwater bodies or surface water bodies. In the EU DWD, no reference has been made to rainwater or RWH as a source of drinking water. As such, the EU

DWD does not give a clear framework for the use of RWH for drinking water supply. At national level, the Dutch drinking water decree (Drinkwaterbesluit, DWB) (Wetten.nl - regeling - Drinkwaterbesluit - BWBR0030111 2024) does not allow the use of harvested rainwater for applications other than toilet flushing. Concerning drinking water, only surface water and groundwater are mentioned as raw water sources. Based on this, the monitoring program for the raw water source used for drinking water production only covers surface water and groundwater. In the Dutch drinking water regulation (Drinkwaterregeling, DWR) (Wetten.nl - regeling - Drinkwaterregeling - BWBR0030152 2024) a division is made between large and small supplies ($<100\ m^3$/day). The monitoring program for these small supplies has lower monitoring frequencies for the quality parameters, but also for these small supplies only surface water and groundwater are considered as raw water sources. Both the EU DWD and the Dutch DWR are not clear on how to deal with rainwater as a drinking water source, either in the risk assessment and risk management of the catchment areas or in the monitoring program of the rainwater as a raw water source.

Despite the growing attention to RWH for drinking water production, practical guidance on its implementation is lacking. The World Health Organization (WHO) and the International Water Association (IWA) have jointly developed a Water Safety Plan (WSP) manual to provide a comprehensive risk assessment and risk management approach for ensuring the safety of the entire water supply system, from source to tap (World Health Organization 2023). This manual provides clear, step-by-step guidelines addressing the safety of drinking water concerning its quality, acceptability, and quantity. While the applicability of the WSP manual extends broadly to all types of drinking water sources and drinking water supplies, its primary focus is on piped water supplies managed professionally. Consequently, WHO has augmented its offerings by releasing two distinct guidelines tailored specifically for small-scale drinking water supply systems: 'Water Safety Planning for Small Community Water Supplies' (World Health Organization 2012) and 'A Field Guide to Improving Small Drinking Water Supplies' (World Health Organization 2022a). The WSP guidelines emphasize the pivotal role of monitoring control measures and the verification of WSP effectiveness (World Health Organization 2023). While these guidelines can be applied to both new and existing schemes, there is a notable lack of clarity and detail regarding proper monitoring control.

Besides, various regulations and guidelines, such as the WHO's Guidelines for Drinking Water Quality (GDWQ) (World Health Organization 2022b), outline detailed requirements for drinking water quality. Additionally, different regions have developed monitoring standards tailored to their specific circumstances. However, the water quality monitoring legislation addressing situations where rainwater serves as the source of drinking water is currently lacking. In the case of RWH systems, existing parameter monitoring requirements outlined in drinking water legislation can serve as a foundation for reference. Nevertheless, due to the diverse sources of water and varying scales of water supply systems, adhering entirely to drinking water legislation for compliance monitoring may prove costly, less credible, and less practical. Consequently, it is essential to adapt the compliance monitoring plan to align with the unique characteristics of rainwater sources. This ensures a more effective and appropriate strategy for monitoring and maintaining drinking water quality standards in RWH systems.

This paper describes a framework for how to build a water quality monitoring program for RWH systems used for drinking water production. It aims to address the gap mentioned above by providing detailed instructions for establishing a comprehensive and secure monitoring program. This framework encompasses monitoring control measures and outlines how to verify the effectiveness of WSP, specifically tailored for new drinking water systems utilizing rainwater as the primary source. It is crucial to highlight that, in this context, the RWH system under consideration serves as a decentralized drinking water supply system operating at the community scale. A project called Superlocal in Kerkrade, a city in the Dutch province of Limburg was used as a case study to apply the monitoring framework construction method. In the project Superlocal, rainwater is collected from a community-size residential area and is treated to drinking water for the local population at a small-scale water treatment plant within the project.

Besides studies focusing on the water quality risks of RWH, many studies have been carried out into decision-support frameworks to understand the potential for deploying RWH decentralized water technologies. These studies focused on aspects such as energy, cost, and greenhouse gas emissions (Arora *et al.* 2015; Morales-Pinzón *et al.* 2015). There is some literature about the economic feasibility of RWH systems, but the conclusions vary significantly. The viability of RWH systems is influenced by their size, with apartment-scale systems often proving more economically feasible than those for single houses (Morales-Pinzón *et al.* 2015; Pacheco & Campos 2016). In a study by Freitas & Ghisi (2020), 57.4% of RWH systems were deemed economically viable, yet the collected rainwater was only used for non-potable purposes like toilet flushing, laundry, and gardening. However, utilizing rainwater as a potable water source increases production costs. Environmental conditions also impact economic viability. In a household-scale RWH for drinking water in Australia, centralized water supply was absent and residents had to buy water from the store (Alim *et al.* 2020a). It was concluded in that study that RWH systems are more economically viable compared to buying drinking water in-store. In the economic analyses of rainwater as a drinking water source, investment costs, including water treatment, are typically considered. However, detailed studies on water quality monitoring and testing costs are missing.

In addition to irrigation and flood mitigation applications, RWH for domestic urban uses has been discussed as a climate adaptation strategy for the last two decades (Pandey *et al.* 2003; Kahinda *et al.* 2010; de Sá Silva *et al.* 2022). However, as outlined in the IPCC's Sixth Assessment Report (AR6) (Caretta *et al.* 2022), adaptation strategies need to be action oriented with a broader scope of considerations; in the context of safeguarding water quality, we therefore find a need to assess the feasibility, effectiveness, and costs and benefits of rainwater harvesting systems in specific contexts, including water quality regulations for health. Similarly, AR6 emphasizes the importance of analyzing financial implications of the adaptation in the context; in our case, if uptake happens at scale in the Netherlands, we need to carefully assess the costs of RWH infrastructure and operational cots of water quality monitoring, together with exploring potential subsidies that could support uptake. This paper employs Superlocal as a case study not only to apply the framework to build the water quality monitoring plan but also to analyze the economic feasibility of a RWH drinking water supply system at the community scale, encompassing investment and water quality monitoring expenses, as well as recommendations for financial incentives.

The article is organized as follows. In Section 2, we first outline the general methodology, where based on the WSP ideals, we derive an approach tailored to RWH drinking water supply systems. The methodology of economic feasibility analysis of the RWH system is also introduced in this section. We then apply the framework in the specific context of the Netherlands in Section 3. Based on these results, we discuss points related to parameters, regulation, and economic feasibility in Section 4. Finally, Section 5 summarizes our findings and points relevant to policy.

2. FRAMEWORK FOR BUILDING A WATER QUALITY MONITORING PLAN AND ECONOMIC FEASIBILITY

2.1. Framework for building a water quality monitoring plan

The WSP manual (World Health Organization 2023) and the WSP guide for small community water supplies (World Health Organization 2012) provide detailed and step-by-step instructions about how to ensure water safety for different sources. In principle, RWH drinking water supply systems can also follow the same broad instructions of these manuals. There are 10 modules in WSP and 6 modules in WSP for small communities as shown in Table 1. Based on these modules we have developed a framework that includes 5 tasks tailored to the RWH drinking water supply system to ensure water safety.

The five tasks of our new framework are shown in Figure 1. Task 1 involves gathering comprehensive information to describe the RWH water supply system. Accurate, detailed, and up-to-date water quality, quantity, and legal information from source to tap should be collected. Task 2 defines the monitoring parameters which include monitoring locations, parameters that need to be monitored, and the acceptable values for parameters. Task 3 involves determining the monitoring frequency and timing based on legislative requirements, rainwater quality, treatment methods, and drinking water production capacity. Task 4 delves into determining monitoring techniques. Task 5 focuses on data storage and analysis. These tasks in the framework for building a monitoring program should be iterative and not a one-time process. Continuous adjustments and updates to monitoring control measures are essential in response to environmental changes and emerging measurement data. The framework does not cover the selection of treatment options nor does it discuss, argue, or question quality standards. Treatment options have been described in literature extensively (Raimondi *et al.* 2023) and the treatment used in a RWH is considered as a given fact in the development of the monitoring program. Below is a more detailed explanation about each task.

2.1.1. Task 1. System information

Task 1 involves gathering comprehensive information to describe the water supply system using RWH. A detailed system description can help understand the system and make a more suitable and safer water quality monitoring plan. The description should be accurate, detailed, and up-to-date because system information is the basis of the monitoring plan. It may, however, not be possible to fully characterize the system area at the outset. Therefore, it is still possible to adjust and add more information later (World Health Organization 2012). Table 2 summarizes

Table 1 | Modules of the water safety plan by WHO-IWA (World Health Organization 2012, 2023).

WSP component	Module	WSP	WSP for small communities
Preparation	1	Assembling the WSP Team	Engage the community and assemble a WSP team
System assessment	2	Describing the system	Describe the community water supply
	3	Identifying hazards and hazardous events	Identify and assess hazards, hazardous events, risks and existing control measures
	4	Validating existing control measures and assessing risks	
	5	Planning for improvement	Develop and implement an incremental improvement plan
Monitoring	6	Monitoring control measures	Monitor control measures and verify the effectiveness of the WSP
	7	Verifying the effectiveness of water safety planning	
Management and communication	8	Strengthening management procedures	–
	9	Strengthening WSP supporting programs	–
WSP review and improvement	10	Reviewing and updating the WSP	Document, review and improve all aspects of WSP implementation

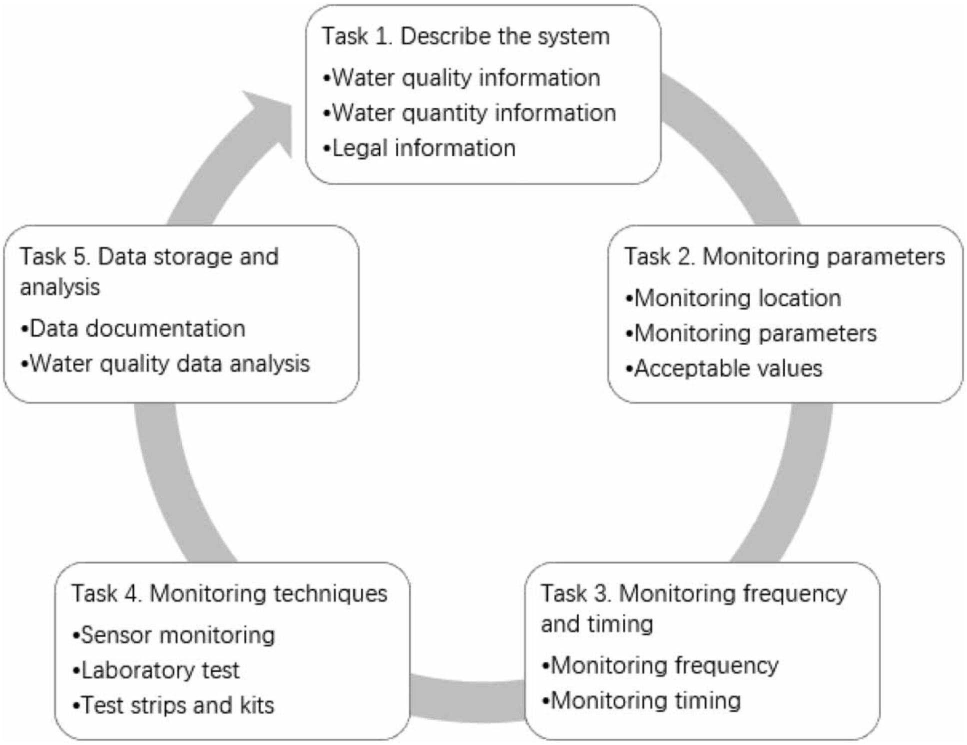


Fig. 1 | Tasks in the framework for building a monitoring program for a RWH-based drinking water supply. The tasks form a continuous cycle of assessment and updates.

the three aspects of water quality, water quantity, and legal information that a community-scale RWH drinking water supply system should collect from source to tap.

2.1.2. Task 2. Monitoring parameters

Task 2 involves defining the parameters for monitoring the quality of water in an RWH system. This task requires determining the appropriate monitoring locations, parameters, and parametric values. Operational monitoring checks the effectiveness of control measures, while compliance monitoring ensures water quality meets regulatory standards. Sampling and testing typically occur at the source, during and after treatment, within distribution and storage systems, and at the user's tap. In decentralized RWH systems, water treatment and user points are closely linked, reducing potential water quality fluctuations and possibly diminishing the need for repetitive tap sampling if treated water tests guarantee water safety. Therefore, the water quality monitoring locations in the RWH systems can be simplified to source, water treatment, and after treatment.

Parameters and the parametric values for these parameters should be decided by the initial water quality, treatment efficacy, the condition of storage and distribution systems, and existing drinking water regulations. Since no standardized guidelines specifically for rainwater exist, local conditions should guide the setting of these limits, drawing on existing drinking water standards as a reference. Adjustments to monitoring plans should reflect observed data trends, ensuring cost-effective practices that do not compromise water safety or regulatory compliance.

Table 2 | Describe the RWH drinking water supply system.

Stage	Water quality information	Water quantity information	Legal information
Catchment (source)	• RWH plan • Location and land use • Human activities • Climate • Material of roof, road, and pipe • History rainwater quality data	• Harvested rainwater quantity	• Source quality requirement
Treatment	• Treatment process • Treatment ability	• Treatment production capacity	• Water quality after treatment
Storage and distribution	• Material of storage tank and pipes • Storage plan • Water distribution paten • Secondary treatment in a storage tank • Tank cleaning plan	• Tank volume	
User practice	• Water usage patten	• Water quantity demand	• Tap water quality requirement

2.1.3. Task 3. Monitoring frequency and timing

Operational monitoring during the treatment process can be performed online in real-time. Compliance monitoring at the source and treated water can be less frequent than operational monitoring, typically once or twice a year for most parameters, depending on the production capacity of the RWH system. RWH systems are often decentralized systems that require less frequent monitoring by regulation. For new RWH drinking water supply systems, initial comprehensive monitoring is recommended to assess potential water safety issues and establish a basic understanding of water quality. If the monitored parameters are stable and the values are much lower than the regulatory standards, the monitoring frequency can be adjusted in accordance with the drinking water regulations. Consideration should be given to increased monitoring when any changes in water quality may occur in a water supply system. Timing of compliance monitoring should account for temporal variations in rainwater quality, with parameters requiring multiple checks annually distributed evenly across seasons.

2.1.4. Task 4. Monitoring techniques

Monitoring techniques can be chosen in terms of monitoring frequency, monitoring accuracy, monitoring range, response time, costs, and maintenance. Operational monitoring during treatment requires real time. Sensors may be employed for operational water quality monitoring. Tests for the source and treated water can be divided into two main categories: on-site testing and laboratory testing. On-site testing involves parameters such as pH and turbidity, and test strips, kits or sensors can be used. Certain parameters, such as chlorine residue and temperature, must be measured on-site due to their inherent instability (Wetten.nl - regeling - Drinkwaterregeling - BWBR0030152 2024). For most parameters, samples are collected on-site and subsequently transported to a laboratory for comprehensive testing and analysis. This approach ensures thorough examination and precise measurement of water quality parameters.

2.1.5. Task 5. Data storage and analysis

Task 5 focuses on data storage and analysis in the water quality monitoring framework, which is critical to ensuring safe water quality and efficient long-term management of the RWH system. Protocols for safe storage of water quality data can provide a historical record that can be used for compliance verification, long-term system assessment, and even policy development. Advanced data storage systems ensure the integrity, accessibility, and security of data, allowing for efficient data retrieval and sharing among various stakeholders. Together, data analysis and storage form the backbone of a proactive water management system that supports public health and environmental protection. Data analysis enables the identification of trends and anomalies in water quality, essential for timely interventions with respect to source water quality or the effectiveness of treatment protocols. Longer-term data analysis helps adjust collection and treatment methods, improving emergency response capabilities to maintain treated water quality and safety.

2.2. Economic feasibility of an RWH system

The drinking water production costs of an RWH system can be divided into two parts: production costs and water quality monitoring and testing costs which are usually expressed as costs per cubic meter of water. Production costs include initial construction and infrastructure development, and significant investments in water treatment technology, recalculated as yearly interest and depreciation per cubic meter of water. Operations such as maintenance of the treatment process, energy, and chemicals (including membrane replacement and UV lamps) are also part of the production costs. In addition, personnel costs, including wages and the procurement and operation of programable logic controllers (PLCs), are important to efficient facility management and are included in production costs. The costs of water quality monitoring and testing include the purchase of internal monitoring equipment at the treatment plant, the purchase of test strips and kits, and the costs of taking water samples and sending them to the laboratory for testing in addition to the testing at the laboratory.

3. RESULTS: APPLICATION OF THE FRAMEWORK THROUGH THE SUPERLOCAL CASE AND THE ECONOMIC FEASIBILITY

3.1. Framework application for building the water quality monitoring plan

In this section, we develop and apply the framework depicted in Figure 1 using the case study of a specific RWH system Superlocal in the Netherlands. Through the application of the different tasks, we explore both the regulatory, and technical aspects.

3.1.1. Task 1. Describing the RWH system

Superlocal is a decentralized drinking water supply RWH system as shown in Figure 2. It is a 4.25 ha residential area with flats, lawns, a parking lot, and a small-scale drinking water treatment. In the Superlocal case, rainwater from both roof and road runoff is collected. The roofing material is EPDM, which is a non-toxic material that does not pollute rainwater. The piping material is PVC and the pavement and parking lot material is concrete.

In order to maximize the water collected, the system also captures the first flush. The average amount of annual precipitation in Kerkrade is 884 mm. December is the highest precipitation month with 86 mm per month, while April is the lowest precipitation month with 58 mm (https://weather-and-climate.com/average-monthly-Rainfall-Temperature-Sunshine,kerkrade-limburg-nl,Netherlands). There are about 10 rainy days in Kerkrade every month. Therefore, there are no long dry periods that may severely degrade the collected rainwater quality. Because local rainwater quality data were unavailable for the Superlocal case, data from the Dutch rainwater quality database provided by the Foundation for Applied Water Research (STOWA) were used as a reference

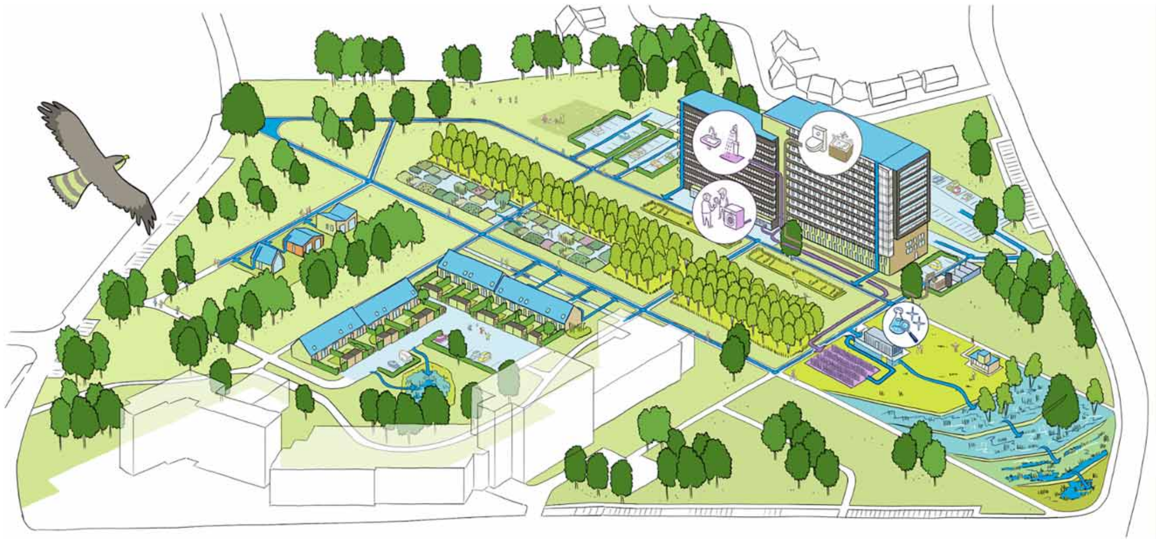


Fig. 2 | Superlocal water cycle plan (source: https://www.superlocal.eu/waterkringloop-2/, accessed on 1 October 2024.).

(Stichting Toegepast Onderzoek Waterbeheer (STOWA) 2020). STOWA collects water quality and rainfall data to monitor the long-term performance and safety of water resources, useful in water management and particularly in assessing innovative pilots like Superlocal. These data are also useful for RWH research as it enables the evaluation of system reliability, treatment effectiveness, and water availability under real-world conditions; for example, the sizing of RWH is done in Shefaei *et al.* (2025) using STOWA rainfall data, which we extend here through its use in assessing water quality.

STOWA database contains rainwater quality data collected from 191 locations in the Netherlands that can be categorized into four types: Companies, City center, Highway and Residential area. The hardening types include Roof, Road, Mixed roof and road, and No hardening. In this paper, the Superlocal case serves primarily to demonstrate how the proposed framework can be applied to determine water quality monitoring requirements. Therefore, the focus lies on the methodology rather than the specific data, and the importance of using local data is emphasized within the framework itself. Since the STOWA database collects rainwater data from across the Netherlands, it provides the best available alternative, as well as an indicator of general quality levels in the country. Specifically, 973 water quality sample data collected from residential areas, focusing on mixed rainwater from rooftops and roads, were selected from the STOWA database to fit the case study, i.e. to align as closely as possible with the category and hardening conditions at Superlocal.

After rainfall, rainwater from roofs and pavement is collected and transported to the treatment plant. Rainwater is then stored in two 125 m^3 rainwater tanks, and water quality parameters such as turbidity in the tanks are monitored. If the water quality meets the requirements (see Task 2), it proceeds to the treatment units. Otherwise, it is directed to the municipal sewer system for proper disposal. The treatment process consists of five steps which include two coarse filters in series, a nanofilter, Ultraviolet and Oxidation (UVOX), an activated carbon filter, and a marble filter. Firstly, two coarse filters with pore sizes of 100 and 30 m effectively eliminate larger particles such as sand, protozoa, giardia, and cryptosporidium from the rainwater. Subsequently, a nanofilter membrane targets particles larger than 10 nm, including humic acids, contagious bacteria, protozoa, and viruses. Following this, the UVOX treatment is used as an additional barrier to inactivate microorganisms, including bacteria and viruses. An activated carbon filter is then utilized to improve the water's odor and taste while simultaneously adsorbing organic compounds. Finally, a marble filter increases water hardness by providing additional minerals such as calcium and magnesium ions. Following treatment, the water is stored in a 50 m^3 drinking water tank for monitoring key parameters such as turbidity and pH before being transported to users (see Task 2). The tank is constructed from concrete, and the transporting pipes are made of PVC. Treated water is transported to users in a short time after treatment.

There are about 130 households with 2 to 3 people in the Superlocal project. Assuming that water demand per capita is 128 liters per day (Vewin association of Dutch water company 2023), the water demand in the Superlocal project is a max of 42 m^3/day. The Superlocal project collects rainwater from 4.25 ha, the annual precipitation in the Superlocal project is 884 mm, and the average runoff coefficient is 0.47. Theoretically, up to 49 m^3 of rainwater can be harvested per day. This calculation has not considered the rain buffer size. There are two 125 m^3 rainwater tanks in the Superlocal project which can collect 12.6 mm of precipitation. This means that if the precipitation is larger than 12.6 mm in a short period, rainwater that exceeds 12.6 mm will not be collected for treatment. Therefore, the actual rainwater that can be harvested is less than 49 m^3/day. If the rainwater is not enough as the source of drinking water, graywater will be used. The graywater will enter an aerated helophyte filter first, and then enter the water treatment plant as shown in Figure 2 (purple color). Treated graywater can be used as toilet flushing as a backup water source if rainwater is not sufficient. The usage of graywater will not be discussed in detail in this paper. According to the dimensions of the treatment units, the drinking water production capacity is about 48 m^3/day. Based on the information above, the drinking water production in this RWH system is about 42 m^3/day.

The use of rainwater as a source of drinking water is not permitted in the Netherlands. The Drinking Water Decree DWB and the Drinking Water Regulation DWR are the two main legal instruments related to the drinking water supply in the Netherlands and are used as monitoring references in the Superlocal case. DWB describes the basic regulations for domestic and household water use in the Netherlands, issues related to drinking water quality, legionella prevention, and water supply continuity and water supply efficiency (Wetten.nl - regeling - Drinkwaterbesluit - BWBR0030111 2024). It emphasizes the requirements for drinking water quality. DWR focuses on source water quality requirements and monitoring requirements (Wetten.nl - regeling - Drinkwaterregeling - BWBR0030152 2024).

3.1.2. Task 2. The choice of monitoring parameters

The DWB states that water quality needs to be monitored in five areas of the process from raw water to tap water: (1) the quality of the raw water, (2) the quality changes in the purification process, (3) the quality of the drinking water after the final purification step, (4) the quality during transportation, and (5) the quality of the drinking water at the consumer's tap. Superlocal is a community-scale drinking water supply system, and water is transported to the customer over a very short distance and time after treatment without additional sources of contamination along the way. Therefore, the quality of the water at the users' tap is considered to be the same as the quality of the treated water. The monitoring places in the Superlocal case only include source water quality monitoring before water treatment, water quality monitoring during the water treatment process, and water quality monitoring after water treatment.

For the source and treated water, water quality monitoring is required to confirm that the water quality meets the regulations and standards which can be called compliance monitoring. According to the DWB and DWR, the parameters that need to be monitored before and after water treatment can be categorized into microbiological parameters, chemical parameters, indicator parameters (operational parameters, aesthetic parameters, and signaling parameters), and radiological parameters. The collected rainwater will not contain radioactive elements, so there is no need to monitor them. In addition, no copper, lead, or zinc pipe material is used in the Superlocal RWH system, so there is no need to monitor copper, lead, and zinc concentrations for treated water. Besides, UVOX is used for water treatment, so free chlorine and vinyl chloride do not need to be monitored for treated water. There are 56 and 45 parameters to be monitored at the source and after water treatment, respectively, as detailed in Supplemental Information (SI) Table 1.

The DWR establishes water quality requirements for groundwater sources and surface water sources. In the Superlocal case, because the first flush will be collected and there is a parking lot in the area, the collected rainwater may have concentrations of turbidity, microbiological pollutants, and petrol above the DWR standards. However, the treatment process ensures that for these parameters the treated water is of sufficient quality to be used as drinking water. In this case, the source water quality requirements refer to the DWR requirements for groundwater and surface water sources. DWB lists standards for drinking water quality. The treated water quality monitoring of Superlocal will ensure these standards are met.

Water quality monitoring during treatment ensures that treatment processes function properly; this is referred to as Operation(al) Monitoring. Monitoring during treatment requires a fast response time. If there are some parameters out of range, the safety of the treated water is not guaranteed. This requires an early warning system in water treatment. The parameters that need to be monitored depend on the specific water treatment scheme. In addition to water quality parameters, in the Superlocal drinking water treatment, tanks' water level should be monitored which include two rainwater tanks, a nanofilter storage tank, a UVOX storage tank, and a drinking water tank. Pressure and flow are two parameters that are important and need to be monitored in all treatment processes. Except for pressure and flow, parameters such as dissolved oxygen (DO), CO_2, electrical conductivity (EC), and pH also need to be monitored to ensure the treatment works properly. All parameters are shown in Table 3. The range of parameters is provided by the Superlocal case.

3.1.3. Task 3. Monitoring frequency and timing: a regulatory basis

Parameters that need to be monitored during treatment need to be monitored in real-time and continuously. The monitoring frequency for the source quality and treated drinking water quality depends on regulations, water production capacity, historical water quality data, and monitored data. The DWR outlines the monitoring frequency for both source and treated water parameters. This frequency is closely tied to the water production capacity. Specifically, when the drinking water production is below 100 m^3/day, the monitoring frequency is set to its minimum level. In the Superlocal case, the water production is approximately 42 m^3/day, so the minimum monitoring frequency will be the reference which is once or twice a year for most parameters.

There are some situations in which the monitoring frequency can be reduced according to the DWR. If the results of samples taken at regular intervals over a period of at least 3 years at locations representative of the entire supply area are less than 60% of the parametric value, the sampling frequency can be reduced referring to the requirement in Annex 3 of the DWR. Furthermore, if the results of samples taken at regular intervals over a period of at least 3 years at locations representative of the entire supply area are less than 30% of the parametric value of the DWR, these parameters can be deleted from the monitoring list. These two rules do not apply to *E. coli*. Besides, the DWR also lists some parameters that only need to be measured once to give a good first impression of the quality of the drinking water such as Arsenic, Benzene, Boron, etc. Based on the DWR, the DWB, and the STOWA database, we applied six rules to make a monitoring frequency plan for source and treated water quality monitoring:

(1) In order to confirm the water quality of the system, all parameters listed in the DWR and DWB will be monitored at least once.

Table 3 | Parameters that need to be monitored in the treatment scheme.

Treatment scheme	Monitoring parameter	Monitoring range	Monitoring device
Rain tanks	Water level in the buffer	<2,100 mm	Water level sensor
	Effluent pressure	1–3 bar	Pressure sensor
	Effluent flux roofs	0–115 m^3/h	Flowmeter
	Effluent flux pavement	0–255 m^3/h	Flowmeter
Coarse filter	Effluent pressure	<0.8 bar	Pressure sensor
	Effluent flux	1.05–2.71 m^3/h	Flowmeter
Nano filter	Water level in the storage tank	<600 mm	Water level sensor
	Filtration pressure	3–5 bar	Pressure sensor
	Filtration flux	2.1–3.5 m^3/h	Flowmeter
	Effluent pressure	1–3.5 bar	Pressure sensor
	Effluent flux	1–2.5 m^3/h	Flowmeter
	Effluent particle number	100–1,000 nm	Particle counter
	Backwash pressure	<2 bar	Pressure sensor
	Backwash flux	<9.5 m^3/h	Flowmeter
UVOX	Water level in the storage tank	<600 mm	Water level sensor
	Treatment pressure	<6 bar	Pressure sensor
	Treatment flux	<6 m^3/h	Flowmeter
	Particle number	0–1,000 nm	Particle counter
Activated carbon filter	Filtration pressure	1.8–2.3 bar	Pressure sensor
	Filtration flux	1.5–2.5 m^3/h	Flowmeter
	Effluent DO	4–10 mg/l	s::can station
	Inflow Oxidation–reduction	0–12 mg/l	s::can station
	Filtration headloss	<0.8 bar	Manometers
	Backwash pressure	<0.5 bar	Pressure sensor
	Backwash flux	<10.71 m^3/h	Flowmeter
Marble filter	Inflow CO_2	<44 mg/l	s::can station
	Inflow EC	0–1,000 μs/cm	s::can station
	Inflow pressure	0.6–1.1 bar	Pressure sensor
	Effluent pressure	<0.5 bar	Pressure sensor
	Effluent flux	1.5–2.5 m^3/h	Flowmeter
	Effluent EC	100–1,000 μs/cm	s::can station
	Effluent pH	7–9.5	s::can station
	Effluent DO	>2 mg/l	s::can station

(2) For parameters that only need to be monitored once to give a good impression, if the monitoring result is below 30% of the parametric value, the parameters will not be monitored anymore. If the result is between 30 and 60% of the parametric value, the parameters will be monitored once every 5 years. If the result is above 60% of the parametric value, the parameters will be monitored once per year.

(3) Because the STOWA database contains 31 years of monitoring data, there are some extremes in it. Therefore, 5% of the extreme data was removed from the data analysis.
(4) For parameters that have historical data in the STOWA database, if both the first monitoring result (rule 1) and the STOWA data (rule 3) are below 30% of the parametric value, the parameters do not need to be monitored anymore. If the monitoring result and data are between 30 and 60% of the parametric value, the monitoring frequency can be reduced to 50%.
(5) For parameters that have no historical data, they will be monitored with the regulation required frequency. If 3 years of monitoring results are below 30% of the parametric value, the parameters do not need to be monitored anymore. If monitoring results are between 30 and 60% of the parametric value, the monitoring frequency can be reduced to 50%.
(6) The monitoring frequency plan is not fixed all the time because it is constantly adjusted and optimized based on the monitored water quality. If the local environment changes and may affect the parameter concentration, the monitoring plan may need adjustment.

The STOWA database includes 19 and 25 parameters that need to be monitored for the source and treated water, respectively, according to the DWR and DWB. After having removed 5% extreme data from the STOWA database, the data were compared with 30 and 60% of the parametric values in the DWR and DWB, separately. Figures 3 and 4 show the percentage of STOWA data compliance with the DWR value and DWB value, respectively, which is part of the data analysis. The vertical axis of the graph shows the percentage of data below a certain acceptable DWR or DWR value, ranging from 0 to 100. The horizontal axis shows the STOWA database monitored parameters, with three columns for each parameter representing the percentage of quality data that comply with the acceptable value in the DWR or DWB (blue), 60% of the acceptable value in the DWR or DWB (orange), and 30% of the acceptable value in the DWR or DWB (gray) in the STOWA data.

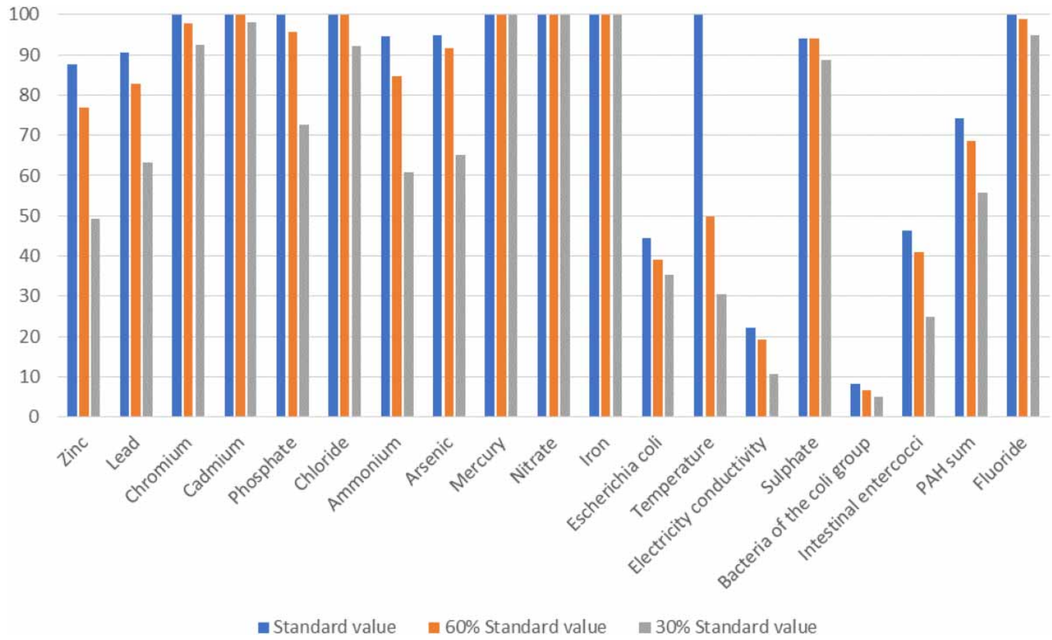


Fig. 3 | Percentage of STOWA data compliance with the DWR value.

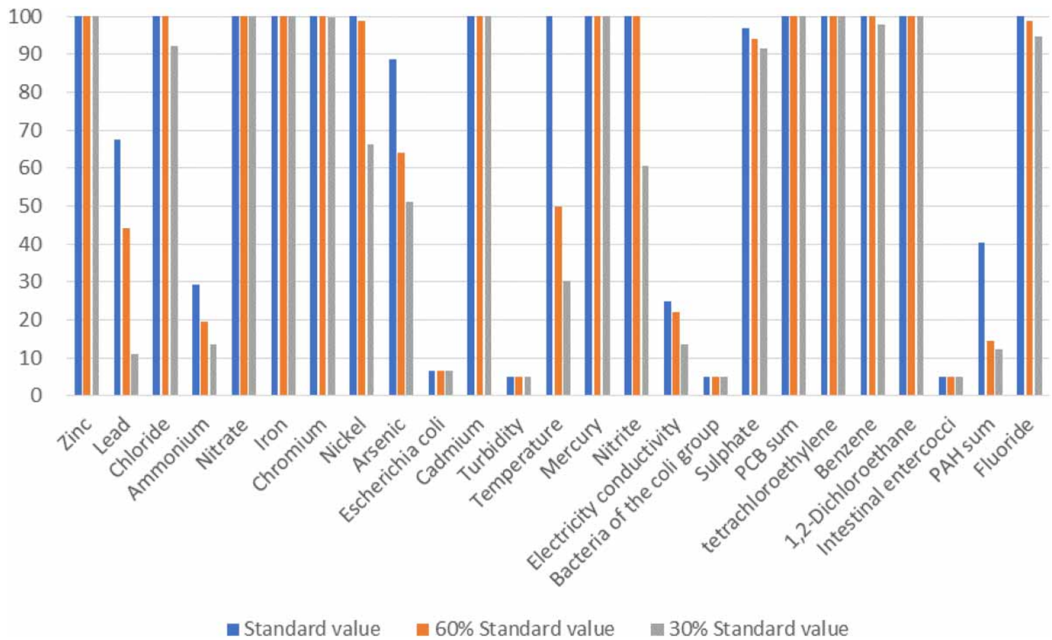


Fig. 4 | Percentage of STOWA data compliance with the DWB value.

Cadmium in Figure 3 is used as an example to show how water quality data influence monitoring frequency: the cadmium acceptable value in the DWR is 1.5 g/l. The orange bar for the parameter cadmium indicates that all monitored data meet 60% of the cadmium acceptable value in the DWR (0.9 g/l), but not all data meet 30% of the acceptable value (0.3 g/l). Therefore, according to monitoring frequency Rule 4 as mentioned above, the monitoring frequency of cadmium in the Superlocal case at the source can be reduced by 50% which is from once a year to once in two years.

As shown in Figure 3, the concentrations of mercury, nitrate, and iron were below 30% of the parametric value in the DWB. This indicates that if initial water quality tests for these parameters remain below 30% of the parametric value, no further measurements are needed for these parameters in the source water. The concentrations of cadmium and chloride were below 60% of the parametric values in the DWB, suggesting that if subsequent tests also show concentrations below 60% of the parametric values, the monitoring frequency for these parameters can be reduced by 50% in source water quality monitoring from the second year.

Similarly, Figure 4 shows that from STOWA data, zinc, nitrate, iron, cadmium, mercury, PCB sum, tetrachloroethylene, and 1,2-Dichloroethane concentrations were below 30% of the parametric values in the DWB. Therefore, if the first water quality tests for these parameters remain below 30% of the parametric values, no further measurements are needed after treatment. Additionally, chloride, chromium, nitrite, and benzene concentrations were below 60% of the parametric values, indicating that if the tests in Superlocal show concentrations below 60%, the monitoring frequency for these parameters can be reduced by 50% after treatment. The monitoring frequencies for all parameters during the first 3 years are detailed in SI Table 1.

Scheduling multiple parameter measurements at the same time can reduce transportation and labor costs. In the Superlocal case, sampling and monitoring can be done in April because April is the month with the least amount of precipitation and the harvested rainwater quality is relatively poor during this period. For parameters that need to be monitored multiple times throughout the year, monitoring can be evenly distributed throughout

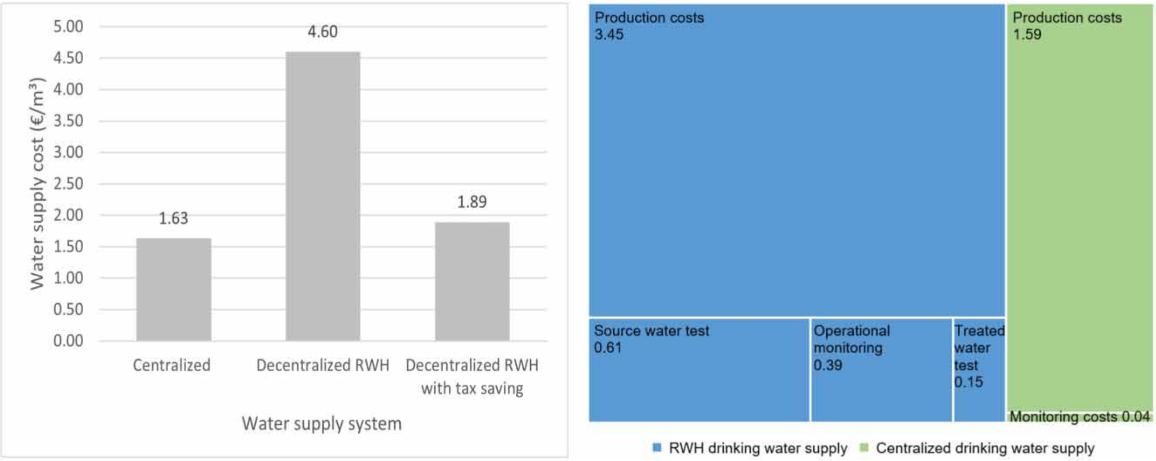


Fig. 5 | Drinking water supply costs in different water supply systems (€/m^3).

the year. In practice, when certain contaminants are detected at concentrations approaching or exceeding the regulatory limits, the DWR requires confirmatory or more frequent testing until results return within acceptable bounds; thus, the occurrence of such findings can temporarily increase the monitoring frequency and cost compared to the baseline plan.

3.1.4. Task 4. Monitoring and testing techniques

Monitoring parameters for the treatment process in the Superlocal case include water level, filtration headloss, pressure, flow, particle number, DO, oxidation–reduction potential, pH, and EC. These operational parameters require fast response and real-time monitoring and will be monitored constantly. Real-time monitoring data will be transmitted to the programable logic controller (PLC), and if there is any abnormality an alarm will be issued to alert the staff to take measures. Monitoring devices include water level sensors, manometers, pressure sensors, flowmeters, particle counters, and a s::can station as shown in Table 3. S::can station includes spectrometer probe, s::can sensor, and s::can control unit. This station can monitor multiple parameters at the same time such as DO, pH, UV spectrum, COD, BOD, benzene, NO_2^-, and NO_3^-. The user only needs to supply the modules with water inlet and electricity; real-time information and parameters will be provided (s::can. nano::station 2021).

There are 64 water quality parameters that need to be tested for source and treated drinking water as shown in Table 4. Forty of these parameters will be sampled at the source or after treatment at the required monitoring frequency (determined in Task 3) and sent to the laboratory for testing. 13 parameters will be sampled at the source or after treatment and then tested at the Superlocal treatment plant using rapid test strips. The corresponding test methods for each parameter are shown in the SI Table 3. The use of rapid tests reduces testing costs compared to laboratory analyses. However, there are two caveats. Firstly, the accuracy of this method of testing is low compared to laboratory monitoring. Secondly, water quality measurement test strips and kits are usually packs of 50–200 tests, and the shelf life is about 3 years. Although the unit price with test strips and kits is cheap, the packages are too large to be used up, because most parameters just require two tests per year for the source and the treated water. 11 parameters will be tested by the scan station in the treatment plant.

Table 4 | Test techniques for parameters need to be tested at the source and treated water.

Test techniques	Parameters
Laboratory test	40 parameters
	Enterococci, Cryptosporidium, (Entero)viruses, Giardia, Campylobacter, Bacteriophages, Legionella, Antimony, Benzene, Boron, Bromate, Cadmium, 1,2-Dichloroethane, Mercury, Nickel, NDMA, PAH (sum), PCB (sum), Pesticides (sum), Selenium, Tetra- and trichloroethene (sum), Barium, Aeromonas (30°C), Clostridium perfringens, Heterotrophic plate count at 22°C, Saturation Index (SI), Hydrogen carbonate, Odor, Sodium, Taste, AOX, Aromatic amines, (Chlorine) phenols, Diglyme(s), ETBE, Halogenated monocyclic hydrocarbons, Halogenated aliphatic hydrocarbons, MTBE, Monocyclic hydrocarbons, aromatics, Other anthropogenic substances
Test strips or kits	13 parameters
	Aluminum, Arsenic, Escherichia coli, Chloride, Chromium, Cyanides (total), Iron, Lead, Manganese, Phosphate, Sulfate, Zinc, Hardness (total)
s::can station	11 parameters
	Electrical conductivity, Temperature, Turbidity, Color, Fluoride, Nitrate, Nitrite, Acidity, Ammonium, DOC/TOC, Oxygen

3.1.5. Task 5. Data storage and analysis

All monitoring data are valuable and should be stored as a Superlocal case database for long-term preservation. Since RWH drinking water supply systems are not yet common, water source quality data is important, and the tested data can be shared with STOWA to enrich the STOWA rainwater database. This can provide data for researchers to study the quality of rainwater in the Netherlands, and can also provide reference data for similar RWHS projects to determine monitoring parameters and frequency. Water quality data will be made available to the public to increase public confidence in the use of rainwater as a source of drinking water. Data analytics can help adjust water treatment processes, such as backwash and disinfection dosage, to ensure optimal system performance. If data anomalies are found during the monitoring process, measures should be taken immediately to find out the cause of the anomalies and solve the problems. Combining source and treated water quality data, source water quality parameterized monitoring standards can be formulated. The frequency of source and treated water quality monitoring can be adjusted by comparing the monitored source and treated water quality with corresponding monitoring standards.

3.2. Economic feasibility of the superlocal case

Water supply costs in the Superlocal case include production costs and monitoring costs. The production costs calculation refers to the calculation method of Hofman-Caris *et al.* (2019) which conducted a city district size study on the economic benefits of RWH for drinking water in the Netherlands. Production costs include Capex, including building costs and water treatment investments; and Opex, including energy, chemicals, membranes, and UV lamps replacement, salary and automation (PLC). According to the water treatment process of the Superlocal case, and corresponding to the price list given in Hofman–Caris's paper, the production costs in the Superlocal case are €3.45/m^3. It should be noticed that in Hofman–Caris's paper, the annual volume of water collected is approximately 64,000 m^3/year which is about four times the amount of water the Superlocal case collects (15,330 m^3/year). Therefore, the exact production costs of the Superlocal case need further study.

The monitoring costs include monitoring during water treatment and tests for source and treated drinking water. Monitoring parameters during treatment include pressure, filtration headloss, flow, water level, particle number, DO, oxidation–reduction potential, pH, CO_2, and EC. Sensor costs and lifetime information are provided by the designer and operators of the Superlocal case. The calculation of the online sensor costs is shown in Table 5. The yearly costs and the average cost per cubic meter are calculated by the formulas below:

$$\text{Yearly costs } [\,€\,/\text{year}] = \text{Price per sensor } [€] \div \text{Lifetime } [y] \tag{1}$$

$$\text{Average cost } [€/\text{m}^3] = \text{Yearly costs } [€\,/\text{year}] \times \text{Number of sensors} \div \text{Water production } [\text{m}^3/year] \tag{2}$$

The drinking water production in the Superlocal case is 15,330 m^3/year, which also includes costs such as for chemicals and energy use. The costs for online sensors are about €0.39/m^3. Unlike in treatment processes of production, the maintenance and energy cost for sensors are negligible compared to the unit costs of the investment; therefore, the costs for maintenance and energy are not taken into account in the calculation for monitoring costs.

Because the monitoring frequency will change over time based on the measured water quality results, the cost analysis for source and treated water testing is calculated using the first year as baseline frequencies. The price list for laboratory analyses was provided by Het Waterlaboratorium (Haarlem, the Netherlands) and is summarized in SI Table 2. In the first year for the Superlocal case, the laboratory testing costs are estimated at €9,192 for source water and €2,197 for treated water. The use of test strips and kits costs €99 for water source and €26 for treated water. Therefore, in the first year, the total cost of testing at the water source and treated water will be €9,291 and €2,223, i.e. €0.61/m^3 and €0.15/m^3.

The estimated costs of producing and monitoring water in the Superlocal case in the first year will therefore be:

$$\text{Water supply costs} = \text{Production costs} + \text{Monitoring costs} = 3.45 + (0.61 + 0.39 + 0.15) = 4.60\ €\,/\text{m}^3. \tag{3}$$

It should be noted here that compliance monitoring frequencies follow DWR regulations. Consequently, if test results consistently remain well below regulatory limits, the required monitoring frequency and the associated monitoring cost can decrease. On the other hand, if parameters approach or exceed regulatory thresholds, confirmatory or more frequent testing may be required. Equation (3) therefore represents a first-year baseline under the under the 100 m^3/day system category considered here, serving as a conservative (upper-bound) cost estimate.

Table 5 | Online sensors monitoring cost.

Sensors	Price per sensor [€]	Lifetime [y]	Yearly costs [€/year]	Number of sensors	Average costs [€/m^3]
Manometers	280	20	14	1	0.00
Pressure sensors	1,206	20	60	10	0.04
Water level sensors	1,685	20	84	3	0.02
Flowmeters	2,870	20	144	10	0.09
Particle counters	9,000	10	900	2	0.12
s::can station	18,500	10	1,850	1	0.12
Total					0.39

4. DISCUSSION

4.1. Framework for building the water quality monitoring plan

The framework proposed in this study offers a flexible approach that can be applied to different RWH drinking water supply systems. Unlike existing water safety plan (WSP) frameworks designed for centralized and regulated surface or groundwater systems, our framework explicitly operationalizes the WSP principles for decentralized, community-scale RWH systems used for drinking water supply, integrating both regulatory questions and analysis of the potential cost of monitoring to meet water quality regulations. This framework represents a methodological advance that bridges the current gap between water safety planning and the emerging practice of decentralized drinking water provision.

However, because each water supply system has unique characteristics such as variations in rainwater quality, production capacity, and legal requirements, individualized analysis and evaluation are necessary. Through the monitoring of water quality following this framework, the data obtained can help with the development of policies and regulatory standards, which are still missing on a European level and in the Dutch drinking water legislation, as described in the introduction. By using the proposed framework for building a water quality monitoring program for RWH systems, the safety of rainwater use for drinking purposes can be enhanced, encouraging greater adoption of RWH drinking water supply systems. Yet, several challenges impede the establishment of legal monitoring standards. Firstly, RWH systems are decentralized, complicating the enforcement and management of consistent quality standards. Secondly, while rainwater collection is widespread, its use for drinking water remains uncommon, resulting in a dearth of relevant water quality data. Lastly, the total costs of community-scale RWH systems for drinking water supply pose a barrier to its widespread adoption.

Ideally, a fully risk-based framework could be developed in the future to design water quality monitoring plans for RWH drinking water systems. However, at present, such an approach is constrained by insufficient data and the variability of rainwater quality across different geographic and environmental settings. In this manuscript, we take a practical approach, which is to collect detailed baseline information on each system, identify and evaluate potential water quality risks, and design a monitoring plan tailored to the specific geographic and regulatory context. As more data becomes available through ongoing operation and monitoring of a built RWH system (eg. Superlocal data after a few years), it may be possible to further develop a model to assess the risk levels of the RWH drinking water supply system.

4.2. Application of the framework

This paper proposes a framework to develop a water quality monitoring plan for RWH-based drinking water supply systems to ensure the safety of the drinking water quality in the water supply system. The five tasks of the framework are System information, Monitoring parameters, Monitoring frequency and timing, Monitoring techniques, and Data storage and system analysis. This framework can be applied to all RWH drinking water supply systems. Following these five tasks, the Superlocal case monitoring plan was developed. Monitoring will take place at the source, during treatment, and in the treated drinking water. According to the regulatory requirements of the DWB and DWR, combined with the data of the STOWA rainwater database, the Superlocal system will test 64 parameters in total, 55 parameters in the water source, and 44 parameters in the treated drinking water in the first year. It is expected that 49 parameters in the water source and 37 parameters in the treated drinking water will be tested in the second year. The test frequency of parameters will be adjusted as the water quality data becomes richer. The parameters that need to be tested, the parametric value of the parameters, and the monitoring frequency are shown in SI Table 1. Monitoring methods include taking samples and sending them to the laboratory for analysis, using test strips or test kits, and testing by a s::can station. 32 parameters need to be monitored during the water treatment process, and these parameters will be measured in real time through sensors. All monitored water quality data will be stored in the Superlocal database. Besides, water source data can be shared with STOWA to enrich the STOWA rainwater database, and water quality data after water treatment can be shared with users to gain their confidence in using this water.

4.3. Economic feasibility of the superlocal case

The cost of producing and monitoring water in the first year of the Superlocal case is €4.60/m^3, which makes the Superlocal RWH economically unfeasible when compared to the price of drinking water in 2023 in Limburg, excluding taxes, of €1.82 (Vewin association of Dutch water company 2023). Looking at the costs of Superlocal, 75% is for production and 25% is for water quality monitoring and tests. This high proportion of monitoring and testing costs is a result of the small scale of the Superlocal system. A given number of analyses have to be done for a relatively small volume of water treated. At a centralized drinking water production scale the analysis costs amount to €0.04/m^3 and contribute only 1% to the total costs (Hofman-Caris *et al.* 2018). In the case study, most parameters in the source and treated water will be sampled and tested in the laboratory, and part of the parameters will be tested by test strips and kits, and sensors. This saves €1,520 euros per year, or €0.01/m^3 compared to sampling and testing all parameters in the laboratory. The frequency of testing some parameters can be reduced from the second year onwards, and as more data becomes available, there may be more parameters that can be tested less frequently, which would reduce the costs of testing.

Two possible options can be proposed for reducing drinking water supply costs using RWH. First, the government can financially encourage RWH. For example, in Berlin, a rainwater tax of €1.81 per square meter of impervious area is payable annually (Khoury-Nolde & Nolde n.d). RWH can be done without tax thus reducing the net cost of RWH. If in the Netherlands, such a rainwater tax would apply, in the Superlocal case the water supply cost could be reduced by €2.27/m^3 as calculated in SI. Second, the water production capacity in the RWH system may be adjusted. According to DWR, if the average water production volume is below 100 m^3/day, only the minimum frequency of water quality monitoring needs to be applied. This means if the Superlocal water production increases from 42 to 100 m^3/day, the testing frequency at the source and the treated water will not change. Therefore, the testing costs for the source and treated water will decrease from €0.76/m^3 to 0.32/m^3. If the above two options can be realized, and assuming that the production costs and operational monitoring costs during treatment per cubic meter water remain the same, the costs for the Superlocal case will be €1.89/m^3 according to Equation (4), which is economically competitive with costs for producing and monitoring drinking water in conventional centralized systems.

$$\begin{aligned}\text{New costs} &= \text{Production cost} + \text{Monitoring and test costs} - \text{Tax saving} \\ &= 3.45 + (0.39 + 0.32) - 2.27 = €1.89\,\text{m}^3\end{aligned} \tag{4}$$

4.4. The future of decentralized drinking water system management and policy considerations

We have shown that the proposed framework is applicable to community-scale decentralized rainwater harvesting (RWH) drinking water systems. However, the management of these systems in practice requires further investigation. Key questions to address include determining the responsible agency for supervision, establishing how effective supervision is carried out, and ensuring efficient oversight. For example, similar nearby decentralized RWH drinking water supply systems may be centrally managed and operated together, which not only improves the safety of the water supply but also reduces water supply costs. Cooperation in source water quality monitoring could work in the Netherlands by following the example of neighborhood energy cooperatives in the Netherlands (Kaandorp *et al.* 2024), which try to collectively reduce energy costs and emissions from household heat demand. The source water quality tests accounted for 53% of total water quality measurements and test costs in the Superlocal case. For multiple adjacent similar RWH drinking water supply systems, the source water quality parameters are not very different, so the source water quality of adjacent systems may also be used as a reference. This may reduce the frequency of source water quality monitoring of these systems and may allow for arranging monitoring of adjacent systems at different times throughout the year. In this way, the frequency of source water quality monitoring is reduced for a single decentralized water supply system, and the system can also obtain water quality reference data from other systems at different times. In addition, monitoring during the water treatment process and treated water monitoring will continue as usual, so water safety can be fully guaranteed. Furthermore, as discussed in the monitoring and testing techniques in Section 2.1.4, some parameters will be tested by test strips and kits, but the large pack size of these test products is a problem. Neighboring RWH drinking water supply systems could share these bulk test strips and kits, or smaller packages may become available in the future.

While this study focuses on the costs and monitoring requirements within the RWH production system and its comparison with centralized systems, it should be noted that in the broader urban water life cycle, end-use processes such as water heating, distribution within buildings, and household use generally account for the highest share of total energy consumption in household water use. The decentralized RWH system primarily affects the source and treatment stages, where its contribution to total life-cycle energy use is relatively small compared to household-level energy demands.

Policy Recommendations: Although prescriptive policy recommendations are beyond the scope of this manuscript, several key considerations should inform future policy development for RWH systems used for potable water. Based on the findings presented in this study, we propose several policy considerations to address the current gaps. First, the proposed monitoring framework or variations, demonstrated through the Superlocal case (Section 3.1), could be formally embedded within permitting procedures for decentralized systems to ensure consistent implementation of safety standards. Second, given the absence of clear EU or Dutch regulations for RWH as a drinking water source (Sections 1 and 4.1), we recommend establishing national-level minimum standards for monitoring parameters and frequencies, with provisions for local adjustment based on system-specific characteristics and monitoring data trends (Section 3.1.3). Third, as discussed in Task 5 of the framework (Section 3.1.5), we advocate for mandatory public sharing of monitoring data and contributions to national databases such as STOWA, which would support regulatory development and benchmarking across systems. Considering the high cost of monitoring per cubic meter in small-scale systems, as demonstrated in the Superlocal case (Section 3.2), economic viability remains a critical barrier. For example, financial incentives, such as tax exemptions on impervious surfaces – similar to those in Berlin – could be considered to enhance the economic viability of RWH systems (Section 4.3). Finally, as highlighted in Section 4.4, cooperative management models inspired by neighborhood energy cooperatives could be promoted and supported by municipal and national governments to facilitate shared monitoring responsibilities. This would also optimize resource use in water quality monitoring across adjacent RWH systems. These together suggest a need for financial mechanisms such as differential taxation policies that recognize the environmental benefits of RWH systems, capital support for community-scale infrastructure development, and regulatory structures that create economies of scale for monitoring and oversight.

5. SUMMARY AND CONCLUSION

This paper presents a novel framework for developing a water quality monitoring plan for decentralized rainwater harvesting (RWH) systems used for potable purposes. Such systems are increasingly considered at community scale as part of climate adaptation strategies for urban water. We therefore need to ensure water quality safety standards for RWH systems, also based on regulatory frameworks. The proposed framework is intended to be replicable in multiple contexts and as such grounded in the principles of Water Safety Plans. It consists of the following five cyclical tasks: system information gathering, water quality parameter selection, monitoring frequency and timing, monitoring techniques, and data storage and analysis. We demonstrate the framework by applying it to the Superlocal case study in the Netherlands, a 4.25 ha residential area with a small-scale drinking water treatment plant.

The case study results highlighted the need for monitoring plans to be tailored to the unique attributes of each location. Crucial considerations included rainwater source quality, treatment methods, drinking water production capacity, and legal requirements. We find that there were no specific general regulations at the EU and Dutch levels for ensuring safety for RWH for drinking purposes. Therefore, the legal basis for the Superlocal case was based on combining aspects of the two existing Dutch Drinking Water regulations, specifically the Drinking Water Decree (Drinkwaterbesluit, DWB) and the Drinking Water Regulation (Drinkwaterregeling, DWR), as reference points for setting monitoring parameters and thresholds. These two regulations, primarily designed for groundwater and surface water sources, were used for the Superlocal system. To comply with the DWB's quality standards, a comprehensive set of 64 parameters need to be monitored for the Superlocal system, encompassing microbiological, chemical, indicator, and radiological aspects. This approach covers source water quality, water quality during treatment, and the quality of treated drinking water. However, recognizing the unique nature of rainwater and the project's small scale (under 100 m^3/day), the regulations allow for monitoring frequency to be tailored. This allowed for reduced monitoring, particularly for parameters where collected monitoring data and initial tests indicated consistently low concentrations parameters compared to regulatory thresholds. The use of these existing regulations, while stringent in quality requirements, provided some flexibility in monitoring frequency, acknowledging the specific context of this rainwater-based drinking water system.

Our application included economic feasibility analysis both for the RWH infrastructure and monitoring. A significant obstacle to the wider adoption of RWH for potable uses is the high cost associated with production and monitoring, particularly at smaller scales. The Superlocal case study estimated a total water supply cost (based on 2023 data) of €4.60/m^3 in the first year, considerably higher than the €1.82/m^3 cost of centralized drinking water in the area. This difference stems from the smaller scale of the Superlocal system, leading to a higher proportion (25%) of expenses allocated to water quality monitoring and testing compared to 2.5% for centralized systems.

As *policy relevant*, this paper considers two solutions to promote the economic feasibility of community-scale RWH drinking water systems as an *adaptation strategy*. Firstly, government financial incentives, such as tax exemptions for RWH systems, could significantly reduce the net cost per volume. If a rainwater tax similar to Berlin's (€1.81 per square meter of impervious area annually) were implemented in the Netherlands, the Superlocal case water supply cost could be reduced by €2.27/m^3. Scaling up production capacity of the system to 100 m^3/day, while maintaining the minimum monitoring frequency stipulated by the DWR, could reduce the monitoring cost per cubic meter. This approach could potentially lower the Superlocal cost to €1.89/m^3, making it more comparable with centralized systems.

Management and coordination of decentralized RWH systems and water quality monitoring also requires attention. Centralized management of RWH systems in close proximity, drawing inspiration from the model of neighborhood energy cooperatives in the Netherlands, could offer advantages in terms of both unit cost reductions and water safety. Collaboration in source water quality monitoring, sharing of test strips and kits, and strategic scheduling of monitoring activities across multiple systems could further enhance resource allocation and cost-effectiveness. The framework presented in this paper provides a valuable tool for establishing comprehensive water quality monitoring plans, a critical step towards ensuring the safe and effective implementation of decentralized RWH systems for drinking water. Addressing the cost and management challenges, in conjunction with robust monitoring practices, can pave the way for decentralized RWH systems to play a vital role in building a more sustainable and resilient water future.

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AUTHOR CONTRIBUTIONS

Y. L. conceptualized the whole article, developed the methodology, investigated the data, was involved in data curation, analyzed the data, visualized the work, wrote the original draft. JPvdH conceptualized the whole article, developed the methodology, wrote the review and edited the article, and supervised the work. E. A. conceptualized the whole article, developed the methodology, wrote the parts of original draft, wrote the review and edited the work, and supervised the work.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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