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Restoring the historical role of chemistry to facilitate universal access to safe drinking water

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Abstract
Freshwater resources are partly polluted by chemicals, and treating them using certain chemicals can have negative impacts on their drinking quality. This communication presents a chemistry-free path to achieve universal access to safe drinking water, with a focus on rainwater harvesting (RWH). Acknowledging that rainfall is freshwater automatically changes the negative perception of rainwater in society. Based on this expected paradigm shift, the communication explores RWH as the sole sustainable solution to address water insecurity issues and achieve several United Nations Sustainable Development Goals (SDGs) within the remaining five years (to 2030). The viability of RWH in the Liesbeek River Catchment (Cape Town, South Africa) is reassessed as a case study. Carefully harvested rainwater is safe to drink in many locations, and in the event that, it is polluted, its treatment using frugal chemistry-free technologies is always possible. Rooftop RWH in the study area can supply the whole of Cape Town with safe drinking water year-round. The findings highlight the relevance of RWH, particularly rooftop RWH, in mitigating drinking water requirements everywhere, not only in water-scarce regions. The communication underscores the significance of well-designed RWH infrastructures for collecting, storing, eventually treating, and delivering rainwater for people's needs.

Keywords Climate resilient, Groundwater recharge, Rainwater harvesting, Stormwater management, Water demand, Zero-runoff approach

1 Introduction

Groundwater and surface water (blue water) are conventionally considered the most accessible sources of freshwater in the world [1–5]. The water demand of the human population has increased considerably due to population growth and changes in human habits. The increasing trend of using groundwater has led to the overexploitation of this water source at many sites worldwide [5–11]. Surface water is also under qualitative and quantitative pressures due to pollution by agricultural, industrial, and municipal activities [1, 2, 4, 12–14]. There is a need for effective conservation solutions to address increasing water insecurity [15–19]. The effectiveness of such solutions depends on a profound understanding of connectivity between the three different freshwater sources on earth: groundwater, rainfall or precipitation, and surface water (Fig. 1) [1, 2, 5, 20–24].

It is essential to recall that water found in surface and subsurface reservoirs (blue water) is ideally precipitation that has percolated into the ground to become accumulated [25–27]. Rivers are formed through the movement of water from higher elevations to lower areas, shaped by geological processes, precipitation, soil moisture, topography, and water table (Fig. 1) [26]. For this reason, precipitation that flows directly into the river (surface runoff, overland flow, or stormwater) can be regarded as a short circuit (shortcut) or an abnormality. In analogy to electricity, short circuits are potentially dangerous issues [28]. A short circuit occurs when electrical current flows through an unintended path with little resistance, often causing damage or even fire [28, 29]. Blue water is the saturated component of the hydrologic cycle, making it concentrated, permanently quantitatively available, and easy for extraction and importation into human agglomerations (imported water). This knowledge has been the driving force for the creation of artificial reservoirs (e.g. dams, lakes, ponds) for agricultural water supply (e.g. irrigation), communal water supply, fishing, flood protection, hydroelectricity, industrial water supply, and recreation [30–32]. At the smallest scale, a cistern or a tank can be regarded as such an artificial reservoir for residential water supply [33, 34]. Depending on the climatic conditions, imported water might be needed as a complement. The key idea of this communication is that small-scale (e.g. cisterns, tanks) and large-scale (e.g. dams, ponds) reservoirs should be complementarily used to optimize (rain)water management. Household reservoirs and small dams are regarded as a powerful tool to avoid any "short circuit" in the transfer of precipitation from the sky to the subsurface (Fig. 1).

Clearly, overland flow or stormwater runoff is operationally regarded as a fault in the water cycle where rainwater bypasses the expected infiltration for increasing soil moisture and aquifer recharge to flow directly into a stream (Fig. 1). This creates a "short" path, often leading to flash flooding, soil erosion, and waterlogging in urban areas

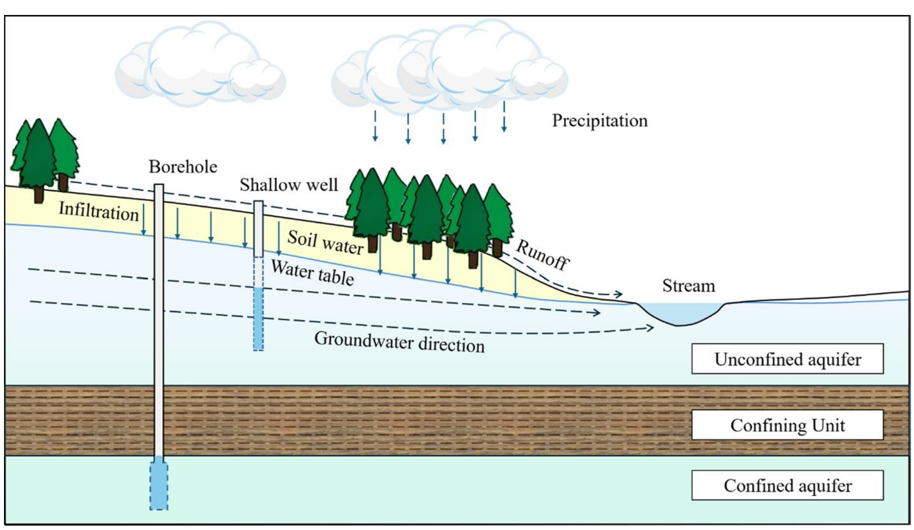

Fig. 1 The three sources of freshwater on earth. Surface water (stream) and groundwater (shallow well and borehole) are secondary sources, coming from precipitation or rainfall (primary source). For the sake of clarity, only the gravity-driven process of precipitation transfer from the sky to the aquifer is represented. Modified after UBA [22]

[34–36]. Summarized, Fig. 1 traces the fate of each rain drop from the sky across environmental compartments to rural and urban agglomerations and, ultimately, to the subsurface (groundwater - well) and to its resurgence as surface water (stream). The illustration in Fig. 1 is intentionally limited to natural systems without polluted water sources (e.g. brackish water, naturally polluted groundwater, saline water, and wastewater). In other words, Fig. 1 recalls that precipitation is the primary source of water on earth, while groundwater and surface water (blue water) are just secondary sources [18, 25, 34, 37–40].

The conventional approach of water management, originating from the development of the first modern crowded cities (e.g. Amsterdam, London, Paris) around the 1850s, is based on centralized water supply with rainwater being drained as quickly as possible out of the city: "rain to the river" [4, 41–44]. Corresponding water infrastructures are designed and managed on a large-scale centralized form incorporating water supply, wastewater, and surface water treatment and distribution processes [1, 45–49]. In such a system, long-distance delivery of water causes considerable energy consumption and high capital cost [50–54]. This makes centralized water supply prohibitively expensive for low-income settings, not only in the developing world [2, 12, 18, 40, 52, 55–58]. For these reasons, decentralized water supply systems have been increasingly developed and implemented [14, 15, 24, 40, 46, 58, 59]. In this framework, rainwater harvesting (RWH) systems have been developed either at the household or community level [2, 15, 35, 40, 58, 60–64].

Household RWH (hRWH) and its subsequent use within the property are increasingly acknowledged to be an underutilized water resource [2, 35, 36, 56, 65–68]. However, while it is certain that hRWH increases the resilience of urban water supply systems [69] and decreases the pressure on the urban drainage system [70], this technology is mostly regarded in urban areas as an approach to supply only water for non-potable uses (e.g. cleaning, cooling, irrigation, laundry, and toilet flushing) [65, 67, 71]. For example, Notaro et al. [65] explicitly stated that hRWH cannot supply water for "all domestic uses". This consideration makes rainwater harvesters dependent on at least one other conventional water source (e.g. bottled water, groundwater, or piped water). Thus, water self-sufficiency can only be achieved using multiple technologies [65]. This perception is alien to millions of people living on small islands where rainfall is the only "perennial" source of freshwater [66, 72–77]. For example, rainfall is the only source of freshwater on Merbau Island (Indonesia) because of the low quality of conventional water sources [74, 75]. Such conflicting reports are not in favour of the exploitation of the full potential of RWH for a better water security [34, 64, 78].

The road to universal sustainable water management can be conceptualized as a journey. Every successful journey needs a roadmap to be followed [79]. The concept of integrated water resource management (IWRM) has been such a road map for the past three to four decades with good achievements in form of active beautiful and clean (ABC) waters programme, best management practices (BMP), blue-green cities (BGCs), integrated rainwater harvesting systems (IRHS), low impact development (LID), nature-based-solutions (NBS), sponge city concept (SCC), stormwater control measures (SCMs), sustainable urban drainage systems (SuDS) or water sensitive urban design (WSUD) [24, 27, 47, 48, 57, 68, 80–85]. In essence, these strategies strive for sustainable stormwater management practices, emphasizing decentralized green infrastructure and water retention. It is about mimicking natural hydrological processes (e.g. infiltration, evapotranspiration) to reduce runoff (stormwater) and enhance water retention in urban areas. Our research group has recently criticized IWRM for not being rooted in the mass balance of water [35] and introduced the zero-runoff approach ("rainwater first") as the missing puzzle [33, 34, 36, 86]. The zero-runoff approach is citizen-centred, considers each house as a water management/production unit, and needs sensitization campaigns. Moreover, the zero-runoff approach is focused on precipitation capture (e.g. "using every drop" or "avoid surface runoff") and not on stormwater management. For this innovative concept, "mimicking natural hydrological processes" starts by intensifying infiltration. This communication aims to provide a "citizen roadmap" for the universal application of the zero-runoff approach, taking the residential areas of the Liesbeek River catchment (Cape Town, South Africa) as a case study [2, 61].

The article is organized as follows: after the current introduction, a brief presentation of the zero-runoff approach (Sect. 2), and details for its application at the household level (Sect. 3). Section 4 then discusses the viability of the zero-runoff approach in the residential areas of the Liesbeek River Catchment, Cape Town. Conclusion and recommendations (Sects. 5 and 6) close the presentation.

2 The zero-runoff approach

2.1 Conceptual aspects

There is a dire need to improve the efficiency of integrated water resources management (IWRM) in addressing water challenges [49, 56, 68, 84, 87–89]. The UN Sustainable Development Goals (SDGs) is expiring in just 5 years (2030), but IWRM, as currently understood and applied, has left many communities around the world with challenges, including access to safe drinking water, access to clean sanitation, and water-related disasters (e.g. biodiversity loss, ecosystem loss, flooding). This sad situation has motivated questioning IWRM at the ground level, as it has been the major water management paradigm for more than 30 years [18, 47, 48, 56, 68, 88, 90, 91]. A careful review of IWRM revealed that it was primarily concerned with redistributing water resources from secondary sources (blue water) among different stakeholders, while considering the economic and social aspects of it [47, 48]. Moreover, it was about finding effective strategies to (i) manage stormwater, (ii) enhance water retention, and (iii) reduce flood risks in urban areas [3, 92, 93].

Table 1 compares the current approach of IWRM with the innovative one [34–36] on which this article is built. It is seen that past and current approaches for water management have overlooked the key role of RWH as a "water creation" process [94, 95]. In fact, the "rainwater first" approach regards rainfall as a valuable resource to be quantitatively harvested, stored, and infiltrated. Ideally, harvested rainwater is locally (e.g. at allotment-scale, farm-scale, residential-scale) stored and infiltrated to the extent that no single drop of water falling from the sky leaves the allotment as surface runoff [96–99]. Basically, it is not essential whether water is stored or infiltrated, meaning that the tank volume can be zero (no cistern, no pond, no tank) and the "zero-runoff" goal achieved through infiltration devices only [34]. This extreme case corresponds to managed aquifer recharge (MAR) at an allotment-scale. This statement alone reduces or relativizes the weight of water quality in considering the adoption of RWH at the residential scale. In other words, rainwater should be harvested whether it is used as drinking water or

Table 1 Key features of conventional water supply, conventional IWRM, and the rainwater-first (zero-runoff) approach(adapted from Gleick [103])

Feature	Conventional water supply (pre-IWRM baseline)	Conventional IWRM	Rainwater-first IWRM (zero-runoff approach)
Water sources	Surface water and groundwater (blue water)	Blue water, desalinated water, recycled water, stormwater, rainwater	Rainwater, recycled water, blue water
Priority source	Blue water	Blue water	Rainwater
Role of other sources	Blue water is the sole reference source	Rainwater and recycled water complement blue water	Blue water serves as a supplementary source
Stormwater management	Discharged after generation	Managed through drainage and partial reuse	Prevented at source through infiltration and storage
Governance regime	Centralized	Hybrid (centralized and decentralized)	Decentralized
Knowledge base	Technical and scientific	Technical and scientific	Integrated formal, indigenous and local knowledge
Guiding principle	"Rain to the river"	"Rain in the city"	"Rainwater first"

BW = blue water (surface water and groundwater); RW = rainwater. The pre-IWRM baseline represents largely centralized systems dependent on blue water. The zero-runoff approach emphasizes minimizing stormwater generation through upstream capture, storage and infiltration. The guiding principles are heuristic expressions used for conceptual clarity

not. Moreover, rainwater should be quantitatively harvested and locally infiltrated, even before the installation of storage infrastructures (reservoirs) becomes financially possible [34–36]. The major innovation of the "zero-runoff" approach is that "infiltrating" and "storing" have primarily the same weightage. The extent of rainwater storage (tank capacity) is still important, but secondary. It is anticipated that coordinated RWH according to the "zero-runoff" approach across residences, clustered residences, and communities allows the full realization "using every (last) drop" [100–102] everywhere rain falls, not only in semi-arid regions.

Stormwater and wastewater are two actual sources of water supply considered in efforts to alleviate water scarcity, according to the conventional IWRM. The merit of the One Water Concept [47, 48] is to recognize all water sources as a single, interconnected resource (One Water). The three explicitly involved sources are: (i) drinking water, (ii) stormwater, and (iii) wastewater [92]. The presentation above has recalled that drinking water is a fraction of the blue water that has been imported into the city. In other words, wastewater contains "imported water". On the other hand, urban wastewater also encompasses stormwater [40, 47, 58, 92]. Clearly, the zero-runoff approach automatically eliminates the two major plagues of urban water management by avoiding stormwater, while storing rainwater for utilization as a primary source of domestic water (instead of "imported" blue water) [34, 93]. Rainfall is thus utilized ("first use") and reused (recycled - "further uses") in the preservation of water resources. The fact that rainwater is not a predictable source of water is implicitly considered (tank size), while reducing pressure on blue water is obvious. The life cycle of all sources of freshwater, according to the conventional IWRM (blue water and rainwater) is extended, and adaptation to climate change is enhanced.

The presentation until here suggests that the many reported discrepancies and ineffectiveness of RWH infrastructures have a more fundamental root. For example, it is not intuitive to consider that RWH is too expensive for households in developed countries [68, 104, 105] yet still suggest it as an alternative for low-income communities [2, 85, 104, 106]. Moreover, it has been controversially discussed whether RWH can assist in flood control through attenuating peak flows and reducing runoff volumes [2, 107, 108]. However, from a pure mass balance perspective (Lavoisier Principle), if there is no peak flow attenuation, then the amount of water harvested is not significant. This statement is valid even for the case of the heaviest rain event. All that is needed is to increase the number and the size of reservoirs (e.g. cisterns, lakes, ponds, tanks). It should be kept in mind that RWH always provides peak flow attenuation but corresponds to stormwater management. The zero-runoff approach advocates for avoiding the generation of stormwater, rather than struggling with its increasing volume [35, 36, 109]. In other words, it is about installing enough rainwater reservoirs and infiltration devices to change the catchment hydrology by nullifying long-distance surface runoff (Table 1). Long-distance surface runoff refers to the evidence that runoff from roads and other impervious surfaces cannot be avoided. Thus, like rooftop rainwater, roadside rainwater must be collected and directed into storage devices, for example, on a kilometre basis [34, 110].

Note that there is no rigid distinction between conventional IWRM and the zero-runoff approach, since some current applications of the conventional IWRM correspond to the zero-runoff approach [16, 68, 97–99, 111–113]. For example, the "net zero urban water" concept for urban water governance [113] can be regarded as an extension or an advancement of the zero-runoff approach. This is because the "net zero urban water" concept does not limit the water sources to rainfall, but rather to all water sources available within the city [114]. On the other hand, Kim et al. [112] demonstrated that by optimizing RWH and greywater recycling, the new community of Filton Airfield (UK) can become self-sufficient in its water supply (circular economy). Also, the integrated rainwater harvesting systems (IRHS) discussed by Choubey et al. [27] to quantitatively capture precipitation and significantly reduce environmental impact correspond to a sort of preliminary version of the zero-runoff approach. This is because an IRHS is explicitly designed to decrease dependence on centralized water infrastructure (not "rainwater first") and reduce energy consumption (e.g. pumping and treating). All these approaches recognize that RWH represents an underutilized but promising approach to increase water security worldwide [27, 54, 68]. They also integrate several functions by combining environmental enhancement, flood mitigation, and stormwater management with water supply.

2.2 Mathematical aspects

The volume of water Q (m^3) that can be harvested from a catchment area A (m^2) with an annual average precipitation P (m/year) is given by Eq. 1 [115]: Runoff volume (Q) = catchment area (A) × rainfall intensity (I – P for the whole year) × runoff coefficient (C).

$$Q = A \times P \times C \tag{1}$$

where C is the runoff coefficient. C accounts for factors like roof type, surface texture, and first-flush losses [116]. Regional rainfall data (P) should be sourced from official meteorological agencies for accuracy.

Q corresponds to the total yearly supply of rain. Q can be used for various demands that are specified here as (i) discharge for flood mitigation (flood), (ii) infiltration (I) to enhance soil moisture and recharge groundwater, (iii) potable (P) for cooking, drinking, and showering, and (iv) non-potable (NP), such as dust abatement, irrigation, laundry, and toilet flushing. Q can be written as follows (Eq. 2):

$$Q = Q_{flood} + \ Q_I + \ Q_{NP} + \ Q_P \tag{2}$$

Equation 2 reveals that, depending on the site-specific characteristics (e.g. P value in Eq. 1), harvested rainwater can satisfy all or only some demands/needs [2, 34, 95]. In dry regions, rooftop RWH may supply only drinking water (Q_P) and eventually water for other domestic uses (Q_{NP}). The governmental 1-2-1 projects in the Gansu province (north-central China) had extended the catchment areas with plastic sheeting for concentrating more rainwater runoff [117, 118]. In humid regions, there can be a need to discharge a fraction of rooftop harvested water (Q_{flood}) to create space for the next rainfall, despite intensive infiltration (Q_I) [42, 119]. The current practice of IWRM has not (properly) considered Eq. 2. This is because different stakeholders have independently considered the individual components of Q.

The municipality, as one stakeholder, is concerned with the collection, conveyance, and treatment of water contaminated by use (wastewater) and non-harvested rainwater that runs off all surfaces (stormwater). Its task is to plan, construct, operate, and maintain a sewer network capable of coping with both wastewater and stormwater, even in the event of the heaviest rainfall. The sewer system must reliably discharge the volume of stormwater generated, without failure (e.g. blockage of the pipelines, obstruction of inlets) of the network performance [120, 121]. Despite a century-old technical expertise, the summer 2021 flooding events in Central Europe (Belgium, Germany, Luxembourg, and the Netherlands) have demonstrated the limits of the drainage-based paradigm [121–123]. Therefore, the alternative view of nature-based solutions is being further developed and implemented [3, 34, 40, 58, 85, 104, 105]. Nature-based solutions fully consider Eq. 2 and its individual terms (e.g. domestic, flood, infiltration, potable). The zero-runoff approach ("rainwater first") advocates for the following sequence: (i) maximize Q, (ii) store $Q_P + Q_{NP}$, (iii) maximize Q_I, and (iv) manage Q_{flood} (Fig. 2). Properly managing Q_{flood} comprises storing excess water from individual farms, households, and roads in artificial lakes, community cisterns, or retention ponds [34].

A third mathematical equation (Eq. 3) is needed to complete the reasoning. Equation 3 describes the distribution of rainfall or precipitation (P) in nature (Fig. 1).

$$P = ET + I + R \tag{3}$$

where ET is evapotranspiration, I is the infiltration, and R is the surface runoff.

When rain falls (P), a fraction is evaporated (ET) through a process driven by solar energy, a second fraction is infiltrated (I) into the soil to increase soil moisture and recharge the aquifer (where geological conditions permit), and the third fraction (R) runs to the river and the sea. Equation 3 is widely considered in scientific literature, where ET is sometimes divided into two components: Evaporation and transpiration. Equation 3 is written in this communication to express the evidence that ET, I, and R are not independent parameters as they are interrelated. At a constant P value, maximizing I automatically minimizes R. This corresponds to what happens during usual rain events, when the infiltration capacity of the soil is not exhausted, and almost the whole rainfall volume is infiltrated into the soil. In the case of heavy rain events, on the contrary, I values are minimized, and R values are maximized. However, because the zero-runoff

Fig. 2 Rainwater harvesting from roof and courtyard according to the zero-runoff approach. Rain falling on other areas of the compound is also harvested (not shown). Overflows from all storage tanks are either locally infiltrated or channelled to community tanks. Own design (Huiyang Qiu)

approach considers the annual rainfall, there is enough capacity to prevent stormwater generation, whatever the intensity of rainfall. The only possible limitation is the structural geology, especially in mountainous areas where rainfall-induced landslides may occur [124–126]. For this reason, heavy water reservoirs should not be installed where landslides may occur.

A key feature of Eq. 1 through 3 is that wastewater is not considered (Table 1). Recycling wastewater is rightly regarded as a water conservation approach. If wastewater is treated to drinking standards, it can be considered as "created" or ternary freshwater, just like desalinated seawater [85]. According to Clément [94], "creating" water corresponds to artificially augmenting the freshwater volume. This is also achieved by artificial groundwater recharge. In the sense of Clément [94], RWH alone is already creating water while just relying on conventional or secondary water sources corresponds to "mining" water. In fact, the centralized water supply approach is rooted in impounding rivers to "mine" surface water and pump (energy) it to treatment stations where huge amount of chemicals is used for its treatment to drinking standards [3, 27, 54]. Using groundwater as a source of centralized water supply also corresponds to "mining" natural water. Thus, the zero-runoff additional approach implies saving chemicals and energy.

Summarized, the mathematics of the cycle of water clearly shows the limitations of the conventional IWRM practice. It contains a flaw rooted in a fragmented consideration of RWH, without accounting for the water mass balance (P = 100%).

2.3 Research in progress

The zero-runoff approach was presented by our research group in 2024 (less than two years ago) and has not yet been acknowledged by the research community (68 citations in total - Table 1). Providing users (e.g. governmental entities, homeowners, non-governmental organizations, scientists) with the state-of-the-art knowledge of any innovative approach is key to encouraging the practice of new approaches [85, 89, 110]. For RWH, there is a dire need to disseminate new developments as the technology is ancient, and its further development is impaired by misconceptions (e.g. non-potable uses only, viability of RWH). This section gives an overview of available publications focusing on the zero-runoff approach (Table 2).

The zero-runoff approach was born in a master classroom in Tlemcen, Algeria, during a workshop intended to discuss rainwater harvesting and recycling as a tool to achieve self-sufficiency in water supply on the campus of PAUWES. PAUWES stands for Pan African University Institute for Water and Energy Sciences, including Climate Change (PAUWES). It was difficult for the instructor (corresponding author) to explain to the learners why there are controversial reports on whether (rooftop) rainwater harvesting systems can contribute to urban flood mitigation. Some students were arguing that for heavy rain events rooftop RWH is unable to contain huge volumes of water falling within a few minutes or hours. The instructor had to go back to the Lavoisier Principle (conservation of mass) to convince the class. Applied to RWH, the Lavoisier Principle can be expressed as follows: If the expected volume of water is known (e.g. P value), then corresponding receiving structures (e.g. cisterns, lakes, pits, ponds, tanks, trenches) can be installed. Once the receiving structures are installed, it is not important when heavy rains are coming; they will be stored, even temporarily. For this reason, it is suggested that the infiltration device is designed to be able to capture water from a heavy rain even (e.g. 100 mm).

The authorship of the inaugural paper (Drain or harvest [35]? – first entry of Table 2) was the whole class and some collaborators of the instructor. Some students realized that the inaugural paper was almost silent on how to properly design the corresponding receiving structures. This gave birth to the paper published at Applied Water Science [36] (second entry – Table 2). Fascinated by the new approach, some colleagues of the University of Maroua (Cameroon) applied it to revisit water management on the Mandara Mountains (fifth entry – Table 2). The fourth entry is the first almost independent

Table 2 Bibliometrics of publications on the zero-runoff approach

Anno	Title	Journal	Citations
2024	Mitigating flash flooding in the city: Drain or harvest? [35]	Water Supply	29
2024	Controlling stormwater at the source: Dawn of a new era in integrated water resources management [36]	Appl. Water Sci.	11
2024	Collecte des Eaux Pluviales - Un manuel de sensibilisation [128]	Technical report	5
2025	Mitigating freshwater supply shortages in regions of high demand in Ethiopia: integrated water resources management approach [127]	Environ. Earth Sci.	15
2025	Revisiting water resources management in the Mandara Mountains [95]	Heliyon	7
2025	Collecte des Eaux Pluviales - Un second manuel de sensibilisation [129]	Technical report	0
2025	An evergreen rainwater harvesting paradigm: "A house wife approach" or the missing puzzle of the "One water approach" [33]	Conference	1
2026	Metallic iron, (rain)water and the city: A handout for researchers and policymakers [34]	Hydroecol. Eng.	0

Citation numbers are from google scholar (https://scholar.google.com/, Access 29/04/2026) journal article on the application of the zero-runoff approach. In fact, Messele Gebre-eyesus (Paper 4 [127] in Table 2) was looking for ways to mitigate freshwater supply shortages in regions in Ethiopia and could be convinced of the efficiency of RWH-based integrated water resources management. The seventh entry is a paper presented at an international conference in Dar es Saleem (Tanzania) in 2025 [33]. It gives the Lavoisier Principle from the perspective of the African housewife which can be translated by the slogan “rainwater first”. The last entry in Table 2 is an invited overview article for Hydro-ecology and Engineering [34] (SCIEPublish - www.sciepublish.com/journals/hee). The remaining two entries are technical documents in French, produced for a Cameroonian non-governmental organization (NGO) [128, 129]. The documents are produced to fill an existing gap in raising awareness on RWH for the French-speaking highland population of West Cameroon and contain many cultural elements.

Thorough awareness and public education campaigns are necessary to sensitize all stakeholders of water management at the outset of the zero-runoff approach. Table 2 summarizes the efforts of our research group, and this communication is a further step in reaching more collaborators for the open proposal of achieving SDG 6.

3 Infrastructures for the zero-runoff approach

3.1 General aspects

The challenges currently hindering the widespread implementation of RWH are widely named in the literature [15, 49, 81, 130, 131]. These factors include the lack of: (i) funding, (ii) regulations, and (iii) technical information about the construction, operation, and maintenance of RWH infrastructures (RWHIs). This communication maintains that the main barrier to widespread implementation of RWHIs is, well, the lack of public adherence owing to a wrong perception of rainwater, namely as a source of pathogens and physical nuisance [35].

Considering the quality as a major challenge of rainwater is non-intuitive for two reasons: (i) rainfall is the cleanest source of freshwater [25, 37, 132], and (ii) the few known contaminants likely to be found in harvested rainwater are easy to eliminate from the aqueous phase, using frugal, chemistry-free solutions [132, 133]. RWH has been successfully used as a non-treatment option for safe drinking water supply where natural waters are polluted by arsenic [134, 135], fluoride [91, 136], and high salinity [137, 138]. Noubactep [128, 129] and Nya [109] recently discussed a path to harvest fit-for-drinking rainwater in Bangangté (Cameroon) based on their knowledge of the local climate. In fact, the period from early August to the end of October is the wettest with regular rainfall. Meaning that from mid-August on, both roof and atmosphere are clean. It suffices to collect drinking water for the whole year in separate cisterns or tanks such as Akkerman Calabashes (Fig. 3) to have in-home safe drinking water for the whole year. Paul Akkerman and Hans Hartung have recalled the suitability of this device to conserve water for the whole year as follows [72, 139]: (i) absence of sunlight (no photosynthesis), (ii) no access to insects and mosquitoes (no health risk), and (iii) access to air oxygen to avoid water decomposition. The Akkerman Calabash has even stopped cholera epidemic in Guinea-Bissau [72]. Clearly, water quality is not a relevant barrier to RWH. Rather, because only a tiny fraction of harvested rainwater is used as drinking water, large amounts of chemicals conventionally used in water treatment plants are saved.

Fig. 3 Photograph of an Akkerman Calabash with a capacity of 5,000 L (5 m^3) in Feutap, Bangangté (Cameroon). A Calabash cistern collects and stores rainwater effectively while being cost-efficient and durable for rural settings. Photo taken by Vanick Fanseu (July 2024)

Moreover, the water user has the choice of the treatment technology and the opportunity to avoid any chemicals like chlorine with its hazardous byproducts [140–144].

The "rainwater first" or zero-runoff concept is multi-purpose in nature (Fig. 2). Depending on the specific objectives to be locally achieved, various volumes of water can be stored. Excess water (overflow) is infiltrated or channelled into community tanks [36], not to any sewage system [34]. Whether or not a fraction will be treated to drinking standards depends on each homeowner. For example, nature-friendly persons living not far from a clean spring would prefer fetching drinking water from there. Other people will prefer drinking commercial bottled water. In all the cases, the whole rainfall is harvested at the compound level, and the household water demand alone fixes the reservoir volumes (Fig. 2). In other words, establishing regional guidelines for potable and non-potable usages of harvested rainwater is still essential but has no influence on the volume of water to be harvested [34, 35]. Clarifying this eliminates the controversial reports on the potential benefits of RWH, while making this method of water supply mandatory for all conscious citizens [35, 50, 51, 110, 145, 146].

With the zero-runoff approach, the scientific literature is enriched with an argument making financial support of RWH more likely. In fact, a citizen harvesting rainfall in his home is not primarily supplying his family with water for all domestic needs. Rather, he does assist the municipality by (i) diminishing environmental effects of urban development on water receiving bodies, (ii) enhancing lifespan of centralized water supply networks, (iii) improving food security, (iv) improving robustness and flexibility of water and energy supply networks, (v) mitigating urban flood (disaster or catastrophe relief), (vi) protecting biodiversity and ecosystems, (vii) recharging groundwater or reducing groundwater depletion, (viii) reducing soil erosion, and (ix) sustaining climate change adaptation strategy [36, 49, 85]. In other words, reducing consumers' water and energy bills is just a side effect of household RWH. While inconsistent evaluation results have been reported related to the economic feasibility of RWHIs, this report advocates for "making rainwater harvesting everyone's matter" irrespective of any economic assessment.

3.2 Design approaches

The design of RWHIs at the household level depends on the current land occupation. The first question to answer is: Is there enough space for storage and infiltration devices? In slums, space may be lacking but for residences, there should be enough space for even several devices (Fig. 2). Where space is lacking, deep tanks and wells should be constructed, eventually added to above-ground cisterns [2, 15, 81]. Alternatively, harvested rainwater from individual compounds is channelled to large community-scale tanks (Fig. 4). In all other cases, it is preferable to have at least three types of reservoirs: (i) one for drinking water, (ii) one for non-potable uses, and (iii) one infiltration device (Fig. 2). Each unit can be a series of several reservoirs, for example, two Akkerman Calabashes

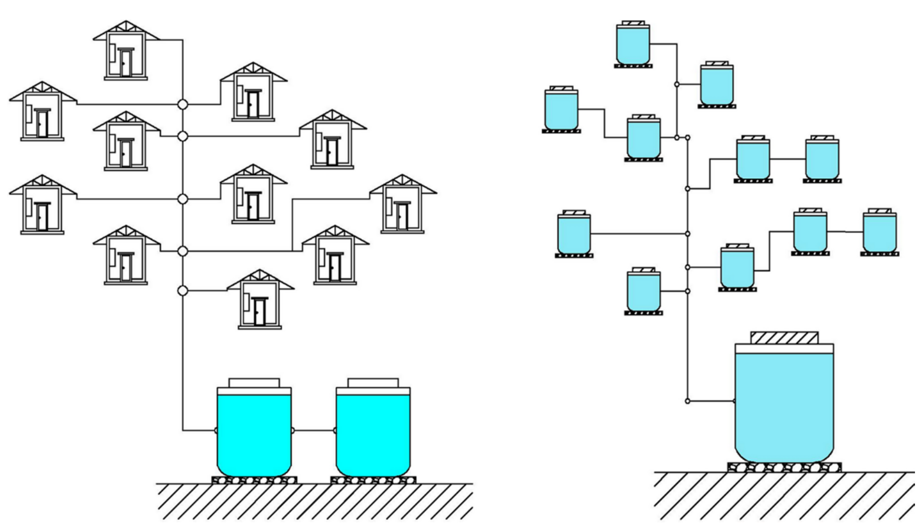

Fig. 4 Flow chart and subsystems of the conventional centralized scenarios for rainwater harvesting at cluster level: in urban slums (left), and in residences (right). Source: Siphambe et al. [36].

for safe drinking water, three reservoirs for non-potable uses, and one or two infiltration wells. The three reservoirs for non-potable uses can separately store water from the roof, courtyard, and garden (Fig. 2). This design reduces the volume of individual reservoirs while assigning their application to specific uses. For example, water from the courtyard can be exclusively used for dust abatement and irrigation of small-scale household nutrition gardens, while water from the cistern garden is used for irrigation only. It is worth noting that once used, water from all three cisterns can be recycled and would correspond to conventional reclaimed water. This recalls that it is a conceptual error to give rainfall or rainwater the same weight as recycled water in the classification of water sources (Table 1). Rainfall is the primary source and only turns to a ternary one (stormwater) when it is not harvested (Sect. 1). Surface water and groundwater are secondary sources of water (Fig. 1).

4 The zero-runoff approach in residential areas of Cape Town

This section aims to reassess RWH for the Liesbeek River Catchment in Cape Town (South Africa) according to the zero-runoff approach. Fisher-Jeffes et al. [2] evaluated the viability of domestic RWH within this urban setting comprising some 6200 domestic properties (average roof area: 200 m^2) in 6 suburbs covering an area of around 1300 ha. The maximum P value (1500 mm/year) is 2.5 times the minimum (600 mm/year). They concluded that RWH was only economically viable for a minority of house owners, while RWH is an unreliable means of attenuating peak stormwater flows.

4.1 RWH potential for Liesbeek River Catchment

4.1.1 Catchment scale RWH

Calculations using Eq. 1 for 1500 mm/year, and a C value of 0.5 (50% harvesting efficiency) show that 26,694 m^3 water can be harvested yearly in the Liesbeek River Catchment, this corresponds to 50 L/day for 533,881 people. Calculations for 600 mm/year give 50 L/day for 213,552 people. These two numbers are just indicative of the non-exploited potential of RWH. Huge volumes of water falling as rain on the Liesbeek River Catchment get lost in the ocean, while everyone agrees that there is water scarcity in Cape Town.

4.1.2 Rooftop scale RWH

While a runoff coefficient of 50% is arbitrarily chosen at the catchment scale, better calculations can be made at the household level: roof area: 200 m^2 and C = 0.9. Calculations for 1500 mm/year show that 270 m^3 of water can be harvested yearly in each household, which corresponds to 50 L/day for 14.8 people. The same calculations for 600 mm/year give 50 L/day for 5.9 people. 50 L /person/day corresponds to twice more water than suggested for the “Day Zero” – the day that Cape Town’s taps would run dry [147, 148]. From that day on, residents would have to collect a daily allocation of 25 L of water at communal water points across the city [148, 149]. If these volumes are multiplied by the number of households, the following values are obtained for 1500 mm/year and 600 mm/year, respectively: 1,674,000 m^3 and 669,600 m^3. The critical implication of these figures is that they represent the volume of rainfall excluded from any form of infiltration and insufficiently considered as driver for depleting groundwater resources. In other words, the 6200 houses of the Liesbeek River Catchment produce a stormwater volume of more than 660,600 m^3 to be drained to the sea. This corresponds to 50 L of water per day for more than 13,392,000 people. For comparison, the current population of Cape Town is only about 4 million, meaning that RWH is a stand-alone solution for safe drinking water supply in Cape Town. As a rich municipality, the city of Cape Town has no problem with draining this water volume to the sea, but Cape Town must realize that this freshwater is exactly what is claimed to be missing [2, 147–149].

4.1.3 Compound scale RWH

The zero-runoff approach advocates for harvesting rainfall from all surfaces within a compound. If an average compound area of 400 m^2 is assumed, the Liesbeek River Catchment (1300 ha) can comprise 32,500 compounds. The total number of households (flat roofs and sloped roofs) is 6200, showing that there is space for commercial buildings, community gardens, driveways, landscaped areas, offices, parking areas, public gardens, roads, schools, sidewalks, soccer fields, swimming pools, tennis courts, undeveloped land, and walkways [61]. RWH must be implemented at all these places to achieve the zero-runoff objective. Ideally, the municipality stores roadside harvested rainwater for street cleaning and firefighting, while municipal lakes and ponds can be disseminated in public gardens and other green spaces. To account for the large evaporation rate between 1300 mm/year and 1550 mm/year across the catchment [2], small and deep open reservoirs should be installed.

It is assumed that the remaining space in each compound (200 m^2) is covered by an 80 m^2 yard and a 120 m^2 garden. Rewriting Eq. 1 for the compound gives the following (Eq. 4):

$$Q = P \cdot [(A_1 \cdot C_1) + (A_2 \cdot C_2) + (A_3 \cdot C_3)] \tag{4}$$

where,

A_1 = Roof area (concrete, metal sheets).

A_2 = Floor covering area - yard (concrete, brick, paving, roads).

A_3 = Untreated soil catchment area (gardens).

C_1 = Runoff coefficient for roof catchments (concrete, metal sheets).

C_2 = Runoff coefficient for yards (concrete, brick, paving, roads).

C_3 = Runoff coefficient for garden (soil).

For calculations, the following values are used: $C_1 = 0.90$, $C_2 = 0.7$, and $C_3 = 0.3$ [150]. These values are selected from a generic list based on the degree of imperviousness and the expected infiltration capacity of the drainage surface [151]. The results summarized in Table 3 give additional water volumes from the yard and garden of 138 m^3 and 55.2 m^3 for 1500 mm/year and 600 mm/year respectively. This makes a total amount of harvestable rainwater of 408 m^3/year and 163 m^3/year for 1500 mm/year and 600 mm/year, respectively. This corresponds to 50 L of water per day for 22.3 and 8.9 people. The average number of persons per household in Cape Town is certainly lower than 8.9, further demonstrating the suitability of RWH for self-reliant water supply for residences in Cape Town. It is recalled that only a tiny fraction of this water must be treated to drinking standards while using frugal and chemistry-free technologies [130, 152–154].

Table 3 Volume of water (Q) harvested in each area within a model compound in the Liesbeek River Catchment in Cape Town (South Africa)

Catchment	*P* (m)	Q (m^3)	Q (m^3/d)	Q (L)	Q (L/d)	People (50 L/d)
Roof	1.5	270.0	0.74	270,000	739.22	14.7
	0.6	108.0	0.30	108,000	295.69	5.9
Garden	1.5	54.0	0.15	54,000	147.84	2.9
	0.6	21.6	0.06	21,600	59.14	1.1
Courtyard	1.5	138.0	0.38	138,000	377.82	7.5
	0.6	55.2	0.15	55,200	151.13	3.0
Total	1.5	408.0	1.12	408,000	1117.04	22.3
	0.6	163.2	0.45	163,200	446.82	8.9

Q is given in different units, and People is the number of persons that can be supplied yearly with 50 L/d

4.2 Integrated water resource management in the Liesbeek River Catchment

The use of harvested rainwater can effectively alleviate the imbalance between urban water supply and demand in the Liesbeek River Catchment. This statement is the common starting point for the works of Dr. Fisher-Jeffes [2, 61] and the analysis in this section. The work of Dr. Fisher-Jeffes was selected for his excellent documentation of all data and parameters necessary for an independent re-evaluation. In other words, the work of Dr. Fisher-Jeffes is an excellent starting point to demonstrate the innovative character of the zero-runoff approach. The comparative analysis given in the next lines is not focused on the limitations of previous works, including those of Dr. Fisher-Jeffes, but rather given as an expansion of continuous efforts to achieve a science-based holistic integrated water resource management and boost the achievement of the long-lasting objective of universal water supply ("adequate water for all" and "every drop counts") [41, 63, 155–157].

The starting point of the zero-runoff approach, or "rainwater first" is: "let's capture the rain when it falls and use it when and where it is needed". To achieve this goal, it is essential to avoid runoff from impervious surfaces (e.g. courtyards, roofs) flowing out of the generation areas (e.g. compounds) and make sure that rain falling on pervious surfaces (e.g. gardens) is captured as soon as the infiltration rate is exceeded. These two approaches prevent the generation of surface runoff or stormwater, which through proper management, has been the cornerstone of conventional IWRM [35, 85, 154]. Clearly, avoiding stormwater generation is the innovation of the zero-runoff approach and explains the differences with the results of Dr. Fisher-Jeffes [2, 61] in Cape Town. The key difference has been to regard rainfall as the mother of all waters on earth, the primary water source (Fig. 1; Table 1). A water source that is renewed every year at a rate of up to 408 m^3 per 400 m^2 compound (or 1 m^3/m^2) under the operational conditions of this work (Table 3). If the used water is recycled at the compound level, this makes more than 1 m^3 of water per m^2 of compound area. A water volume that the conventional IWRM approach is asking whether it is worth harvesting. This consideration further demonstrates the innovative character of the zero-runoff approach or the limits of past and current approaches [49, 110, 148, 149, 154, 158].

Coming back to Fisher-Jeffes et al. [2], it appears that their conclusions that RWH is "only economically viable for a minority of property owners" and that "RWH is an unreliable means of attenuating peak stormwater flows" are untenable for the zero-runoff approach. Concerning climate change, it is likely that its effects have "limited impact on

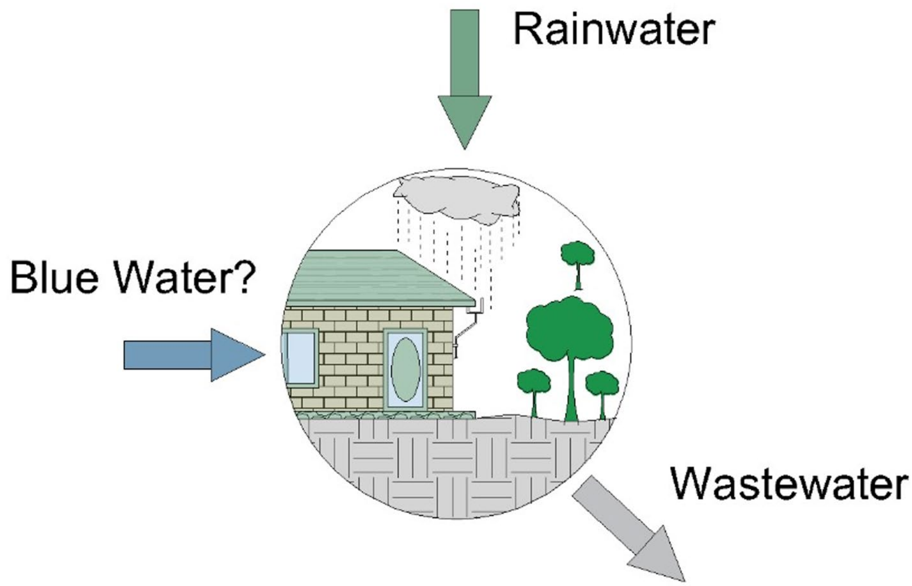

Fig. 5 Illustration of the "rainwater first" at household level. Blue water (groundwater and surface water) is only sought when harvested rainwater (rainwater) cannot satisfy the needs of the household. Resulting wastewater can be treated and recycled. Own design (Bayongwa Samuel Ahana)

the performance of RWH systems". Moreover, the systematic adoption of RWH according to the new paradigm will eventually reverse the negative impact of climate change as progressive revegetation is made possible using excess water (infiltrated or stored) [35, 85, 158]. There is perfect agreement with Fisher-Jeffes et al. [2] on the scope of future research on RWH. In fact, using the new approach, future research should aid in better implementing the (always viable) RWH technology "in different climatic regions of South Africa" and worldwide. In these efforts, social drivers for the broad adoption of RWH should be considered as a priority because the zero-runoff approach needs the participation of all stakeholders to be successful [88]. This will correspond to making water management everyone's matter as it was anciently the case in the terrace system on the Mandara Mountains (Cameroon, Nigeria) [95] or on the hills of India and Sri Lanka [41, 159, 160]. The zero-runoff approach can be regarded as the first attempt to realize the vision of King Parakramabahu of Sri Lanka (12th century), who once proclaimed, "Let not a single drop of water flow into the ocean without being used for human benefit" or "Do not let a single drop of water fall from the sky into the sea" [159]. At the household level, the zero-runoff approach implies using piped water or groundwater only when there is a deficit (Fig. 5).

Clearly, rainfall flows into the sea when it is not harvested (stored/used) nor infiltrated. This is to say that surface runoff or stormwater is an avoidable shortcut of rainfall to the sea. Instead of avoiding this shortcut, the still prevailing approach has unfortunately channelled rain (good freshwater) as quickly as possible to the river (polluted surface water) and to the sea (saline water). Impoundments are then created on rivers to "harvest" river water, treat it with a myriad of chemicals to drinking standards, and pump it into residences. This corresponds to a large misuse of chemistry as a scientific branch, which should have been used to solve pressing issues, not to create avoidable problems [140–143]. This contribution is also an advocacy for green chemistry, starting with "use chemicals only when it is unavoidable" or "use rainwater as it is good freshwater".

It is important to recall that the current IWRM considers RWH primarily as nuisance (stormwater within the trinity blue water/stormwater/wastewater), and only secondarily as a potential water source for non-potable uses (Table 1) [3, 47, 48, 112, 161]. Also, piped drinking water ("imported" water) from a possible distant river or a deep aquifer is the starting point for reasoning. The three main research questions are [1, 15, 81, 161]: How to augment "imported" water? How to conserve it? How to maintain its good quality? These three questions dominate the scientific literature to the extent that publications advocating for large scale RWH as a viable alternative for conventional centralized water supply systems are very scattered or even diluted in the literature [18, 25, 50, 54, 91, 132, 133, 162–165]. For example, Herrmann and Hasse [50] has been referenced only some 67 times according to Google Scholar (accessed 03/05/2026). Herrmann and Hasse [50] is entitled "Ways to get water: rainwater utilization or long-distance water supply? A holistic assessment" and demonstrates that RWH is a viable alternative to centralized water supply. This decades-old "holistic assessment" could have been the cornerstone for mainstreaming RWH.

The presentation herein shows that RWH, according to the zero-runoff approach, is a powerful tool for achieving water security, exploiting every drop of rainfall. Three fundamental challenges are addressed at all scales: (i) enhancing water availability for domestic and productive uses (e.g. conservation of ecosystems, irrigated agriculture), (ii) minimizing or even completely avoiding water's destructive impacts (e.g. drought, flood, pollution), and (iii) avoiding or minimizing the use of chemicals for water treatment. Two important features must be recalled: (i) when rainwater is carefully harvested and stored, its treatment to drinking standard is typically easy to achieve [25, 37, 112, 131, 163], and (ii) when water treated by filtration is to be consumed within some three days, there is no need for disinfection (e.g. chlorination). In fact, in the scientific literature preferred, frugal technologies are those achieving both removal and inactivation of pathogens [37, 59, 166–171]. Disinfection by chlorination has been discouraged because of the carcinogenic disinfection byproducts (DBPs) that are produced by the reaction between dissolved natural organic matter (NOM) and chlorine [140–142]. The NOM content of carefully harvested rainwater is typically very low, and the risk of DBP formation is lower in rainwater than in ground or surface waters. It should be recognized that the absence of essential nutrients (e.g. calcium, magnesium) in rainwater can have health implications if it is the sole source of drinking water. In this case, a balanced diet including vegetables and vitamin supplements is recommended.

Finally, paraphrasing Khanal et al. [55], future investigations on RWH systems should address: (i) how local RWH can positively influence climate change, (ii) to what extent people can completely or partially rely on harvested water at each location, (iii) how to treat harvested rainwater to meet drinking water standards using chemistry-free technologies, and (iv) how to make RWH financially viable (e.g. micro-finances, subsidies) as elaborated by Mwamila et al. [130]. Mwamila [73] dedicated a whole chapter (No. 6) of her thesis to discussing the potential roles of subsidies and incentives in enhancing the adoption of RWH. This makes the affordability of RWH infrastructures the paramount determinant of RWH. Even the variability of rainfall under a climate change scenario is a secondary facet while harvesting and harnessing rainwater. Augmenting water resources will (i) enable landscape restoration, (ii) increase agricultural yields, (iii) reduce hunger and malnutrition, (iv) reduce soil erosion, and (iii) supply safe drinking water not only in developing countries. On the other hand, intensive infiltration will stop and reverse the drop in water reservoir level [172, 173].

5 Mainstreaming residential RWH

Integrated water resource management (IWRM), starting at the household level, is the goal of the "rainwater first" approach presented above. The many uncertainties related to "water imports" from utilities were the major driving force to develop this innovative approach. The net result is an impetus to possibly make each residence self-sufficient with respect to water supply while contributing to an overall improved water management. This result coincides with the opportunity to realize some available visions, including "achieving net zero water", "catching the rain where it falls", "making rainwater harvesting everybody's business", or "using every last drop". The result can also be regarded as the most affordable and applicable path to optimize IWRM. The section prepares the widespread adoption of RWH according to the "rainwater first" approach. It is about facilitating the willingness of citizens to test and adopt a new concept for RWH.

5.1 Designing a residential RWH system

A residential RWH is the unit cell of an integrated RWH system. There are many technical guides and handouts on how to design individual conventional RWH systems [66, 174–178]. These systems are designed for domestic water supply, possibly including drinking water. The "rainwater first" approach maintains this core function while mandatorily adding components for (i) stormwater avoidance (environmental protection, flood mitigation), and (ii) groundwater recharge (water conservation) [34, 36]. Factually, individual residences should implement conveyance paths (e.g. plumbing) for spatial integration by foreseeing a channel to deliver their overflows to neighbourhoods (e.g. community tanks, infiltration and retention ponds).

5.1.1 Technical components

A RWH system typically includes six key components: (i) catchment areas, (ii) conveyance systems, (iii) reservoirs and other storage facilities, (iv) treatment systems, (v) distribution networks, and (vi) monitoring and control systems.

Catchment areas typically include rooftops, pavements (yards), specially prepared surfaces (playground, parking), and pervious surfaces (e.g. gardens). Roof material characteristics significantly influence the quality of harvested rainwater. The catchment material affects collection efficiency, initial water quality, and system maintenance requirements [18, 27, 66, 179].

Conveyance systems (e.g. gutters, downpipes, channels, plumbing systems, and drains) transport water through gravity from catchment areas to storage facilities [27, 66]. A first-flush diverter is mandatory to separate the initial highly polluted runoff, for example, the first 5 mm of each rain event. The conveyance system should also contain filters and screens to remove debris and suspended particles. A properly designed (and maintained) conveyance system minimizes water pollution through diversion of first-flush volumes. Ideally, water from the first-flush diverter is channelled to an infiltration device, but never to a sewage system.

In the conventional RWH, the storage at household level allows bridging the temporal gap between rainfall events and water demand. Relevant reservoirs include composite, concrete, fibreglass, metal, or plastic tanks. These containers may be modular or custom-built, installed above-ground or underground cisterns. Two key features of the "rainwater first" approach are: (i) local managed aquifer recharge should be performed by directing overflows from reservoirs to the aquifer through connected infiltration systems, (ii) the reservoir should be custom-built to ideally store the yearly water demand (not only the days without rain). Systems must be designed to channel excess water to external retention devices such as cisterns, infiltration wells, ponds, rain gardens, swales, and tanks. A rule of thumb is that the infiltration device should be able to retain the amount of water falling during an extreme rain event, for example, 100 mm (rainfall intensity). This precautionary measure allows the system to avoid flooding, even if all tanks were full.

Treatment systems ensure harvested rainwater meets quality requirements for intended uses [134, 179, 180–183]. Treatment approaches include biological filtration, chlorination, filtration through granular media (e.g. activated carbon, biochar, metallic iron), membrane filtration, ozonation, pasteurization, sedimentation, solar disinfection, and UV disinfection. Irrespective of the intended applications, the required treatment level depends on the cleanness and characteristics of the catchment area (e.g. garden, roof, yard), the cleanness of the conveyance system, and the storage conditions. In all the cases, care must be taken to avoid the access of flies, mosquitoes, and ruminants to the reservoirs. Additionally, for a drinking water system, a filtration unit is recommended at the delivery point.

Distribution Networks deliver harvested rainwater to points of use. Water delivery always occurs through gravity systems. In modern residences, elevation differences must be created to initiate gravity flow from an elevated tank to the in-house points of use (e.g. kitchen, toilet). In these cases, electric or mechanical pumps are needed to deliver water to higher elevations. Such minimal power can be easily satisfied by solar energy.

Monitoring and control systems include water level indicators to monitor water availability. Water parameters like microbiology, pH value, specific chemical contaminants, salinity, and turbidity must be routinely controlled. Monitoring enhances system performance while controlling water availability and taking emergency actions, excluding routine maintenance.

5.2 Operating and maintaining a RWH system

Operations and maintenance are basically non-challenging but must be frequently performed by trained personnel [72, 184] (Ma 2015). Relevant operations include (i) cleaning and controlling (regular inspection) the conveyance system to avoid gutter blockages, (ii) controlling the pumping systems to avoid failures, and (iii) inspecting the reservoirs to detect algae growth and eventual signs of cracks, leaks, or wear. Additionally, the functionality of the first-flush device must be frequently controlled, and the reservoirs cleaned yearly or every 2–3 years, using (i) non-abrasive brushes to avoid damaging the tank's surface, and (ii) a non-toxic cleaning solution to scrub the tank's interior. Ideally, a deep clean is performed when the tanks is empty, using environmentally safe products. The long-term reliability of RWH systems depends largely on routine maintenance and access to replacement components. These factors should be known to users before the installation. For this reason, regular maintenance training should be offered to all stakeholders, including cities, governmental bodies, and neighbourhood associations [72].

Ideally, monitoring the quality of stored rainwater and performing the maintenance of the whole residential RWH system should be carried out regularly (e.g. yearly) and documented in a controllable manner. The municipality is the best institution responsible for this mission and should appoint trained personnel for the relevant operations. Another important requirement is the availability of accredited water laboratories [185–187].

5.3 Financing a RWH system

The economic assessment of RWH systems typically includes [27]: (i) capital costs broken down by system component, (ii) operational and maintenance costs over system lifetime, (iii) direct benefits including water savings and reduced utility costs, (iv) indirect benefits such as flood damage reduction, infrastructure savings, and environmental benefits, (v) lifecycle cost comparison with conventional alternatives, (vi) return on investment calculations under different pricing scenarios. It is evident that the economic viability changes with variations in rainfall patterns, installation costs, and water pricing.

A careful look at the operational parameters for economic assessment reveals that such efforts should not be considered while installing RWH systems according to the zero-runoff approach. In fact, the new approach is not comparable to any existing "conventional alternatives" as they are collectively non-holistic, having a centralized water supply system as baseline (business-as-usual). Moreover, the new concept considers aspects like flood risk reduction with the coupled infrastructure and life savings, which cannot be expressed in terms of money. In addition, water is made available in-home, saving family members from many risks while guaranteeing them more time for productive activities, including learning for children [66]. In other words, instead of discussing where money would come from, efforts should be concentrated on motivating governments and non-governmental organizations (NGOs) to make subsidies available. Additionally, the enforcement of the adoption of the zero-runoff approach can be supported by the "polluter-pay-principle". In this case, each residence pays for each cubic meter of non-harvested rain. It suffices for the municipality to install a water meter to monitor the volume of water leaving each parcel.

A last fundamental aspect is that RWH, according to the zero-runoff approach, is futuristic and can be immediately achieved with available skills, even in developing countries (Table 1). Song et al. [34] recently took the example of the city of Yaoundé (Cameroon), extending its supply capacity with Chinese technical expertise to import 300,000 cubic metres per day from the Sanaga River (100 km). The project was completed and inaugurated in 2024, and its initial capacity can be expanded to 400,000 cubic metres [188, 189]. Evaluating the suitability of alternative water sources as adaptation tools to water shortages in Nsimeyong, Yaoundé, Ewang Ahone et al. [190] have not considered RWH. Their conclusions read "a sustainable solution to the shortage of water in Nsimeyong (Yaoundé) seems to be the increased capacity of the existing water plants". These conclusions for humid Yaoundé (> 2000 mm/year) align well with those of Fisher-Jeffes et al. [2] in semi-arid Cape Town (< 1500 mm/year). The net result is that despite three to four decades of discussion on the application of IWRM, some scientists still regard rainwater as a side effect in water management.

Recently (March 2026), the government of Cameroon signed financing agreements worth 111.6 billion CFA francs (111,600,000,000 CFA francs = 198,749,799.65 US $) to support the reconfiguration of the Yaoundé drinking water supply system [189]. Nya et al. [191] estimated the cost of a buried concrete water cistern with 30,000 L (30 m^3) capacity to 2,162,190 CFA francs in Feutap/Bangangté (Cameroon). Meaning that if the Government must fully subsidize tank construction in Yaoundé, assuming the same price in Yaoundé, this will make 51,614 cisterns or water for 361,300 people, assuming an average of 7 persons per household. 361,300 people represent roughly one tenth of the current population of Yaoundé. If we consider the costs of the initial phase (70 billion CFA francs), a total of 83,989 cisterns can be constructed, bringing water to some 587,922 citizens or 15.6% of the urban population. These numbers just indicate the importance of a neglected option. It is not likely that a government will go for 100% subsidies for tank construction. If a 50% is given, the percentage of coverage increases to more than 30%. On the other hand, some rich people don't even need any subsidy. The advantage of RWH systems over the centralized supply option, is that RWH installations have a longer service life and locally creates hundreds of jobs for construction, operation and maintenance.

5.4 Creating awareness for residential RWH

Teaching science and technology requires high expectations in mathematics and natural science to foster creativity and innovation for environmental issues. Singapore has demonstrated the efficiency of this approach by educating its learners to become excellent water and environment managers [15, 192, 193]. For example, in 1987, a water conservation course was introduced at the secondary level to explain Singapore's water challenges and the importance of conservation [15, 81]. Similar initiatives are expected from other countries worldwide. The idea to bring to the classroom can be derived from the following quote, paraphrasing Rosso [88]: "Water supply is more resilient and reliable through rainwater harvesting, groundwater recharge, and wastewater reuse".

This universally valid statement can be completed to: "water supply is more resilient and reliable when rainwater is quantitatively harvested and utilized, a fraction used for groundwater recharge, and wastewater from harvested rainwater reused". Ideally, no other source of freshwater is utilized before rainwater is exhausted ("rainwater first"). Targeted capacity building and institutional integration are needed for the realization of the capacity of the zero-runoff approach for water security. Universities across the developing world should incorporate RWH into architecture, civil engineering, environmental science, and water science curricula. Certified training programs, workshops, and graduate-level courses would help develop the next generation of RWH experts. Mentorship programs linking water practitioners with NGOs and research institutions will also facilitate knowledge transfer. It is about promoting water security or water conservation through three proactive strategies organized around allotment-scale RHW: (i) aquifer recharge, (ii) optimized reservoir operations (e.g. cisterns, lakes, ponds), and (i) wastewater recycling. The difference with current and previous approaches is that RWH is taken from the periphery (e.g. ternary position) to the middle (e.g. primary position) of water management.

6 Conclusion

The future development potential of the RWH industry is discussed in this study using a residential area in Cape Town, South Africa, as a case study. It is shown that, if effectively promoted, RWH would enable (i) water supply for all uses, (ii) the development of a green economy, and (iii) the sustainable development of urban ecological environments. An evolving public awareness campaign and strong policy support are necessary to promote the dissemination of the "rainwater first" approach to the extent that everyone becomes a rainwater harvester. The implementation of the zero-runoff approach can be government-led but never market-driven. In essence, if environmental protection is the primary premise for action, promoting universal RWH and encouraging the local use of recycled wastewater are the path to this overarching goal. The calculations made in this study have demonstrated that the residential areas of the Liesbeek River Catchment in Cape Town have the potential to become self-reliant in water supply. These results represent a U-turn for rainwater management and IWRM as well. This is because they show that limiting the discussion on the economic viability and some specific demands constitutes a conceptual error. Moreover, the conventional IWRM (LID, NBS, SCC, SUDS) is an established approach for stormwater management. IWRM imitates the natural hydrology of a site using decentralized micro-scale control measures. The conventional IWRM emphasizes the use of small-scale, natural drainage features integrated throughout the city to slow, capture, clean, and infiltrate urban stormwater and precipitation. Pollution is thus reduced while aquifers are locally replenished. Harvested rainwater is a tool for locally raising the water table. The "rainwater first" approach goes a step further by avoiding stormwater generation and thus controlling the flux of precipitation from the sky to the subsurface (Fig. 1).

Previous studies have harvested rainwater to locally or regionally balance the water supply and demand. In essence, the attention was focused on a tiny fraction of rainfall, for example, the one satisfying the non-potable demand of a household or the drinking demand of a community. The results of this study demonstrated that previous approaches were reductionist and have overlooked the huge potential of RWH for local and regional development. Irrespective of the climatic conditions, wherever it rains, falling rain should be captured when it falls and used when it is needed. A tiny fraction of harvested rain is treated by chemistry-free technologies to drinking water standards. This corresponds to using chemistry only when there is a dire need.

The results of this study suggest the following two major recommendations:

Introduce rainwater harvesting cisterns and tanks to collect roof runoff and runoff from all areas in all compounds for household demands and groundwater recharge.

Adopt roof RWH as a safe drinking water source in all households and treat the harvested rainwater only with chemistry-free technologies.

These two tools will significantly augment the volume of groundwater while improving its quality after each household has satisfied its needs.

To build the foundation for future research opportunities in implementing the "rainwater first" approach, the following recommendations are made:

Establishing the rules of thumb for the applicability of the concept over different geographic locations (e.g. available skills, climatic conditions, topographic situations).

Establishing metrics and models to evaluate the efficiency of the "rainwater first" approach.

Establishing tools to scale up the residential RWH systems to function at the community scale.

Organizing regular awareness campaigns to encourage citizens and all stakeholders from all over the world to implement the "rainwater first" approach due to its massive societal and environmental benefits.

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Data availability
The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

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The authors declare no competing interests.

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