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Water security and rainwater harvesting at household level in a local municipality in South Africa: quantity calculations and supply implications

Bezpečnosť vody a zber dažďovej vody na úrovni domácností miestnej samosprávy v Juhoafrickej republike: kvantitatívne výpočty a dôsledky dodávok

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Abstract:

The current study seeks to estimate the total yearly volume of harvestable rainwater in Makana Local Municipality. The monthly rainfall patterns were analysed for the 2000-2020 period. The monthly rainfall did not vary with time for ten months in each year of the study period (p-values ranged from 0.1941 to 0.9518). The monthly rainfall increased with time in February (p-value = 0.0497) and decreased with time in April (p-value = 0.0235) between 2000 and 2020. The actual values of the monthly rainfall ranged from 0.0 to 218.4 mm. The completeness of the rainfall data ranged from 75 to 100 %, while its reliability was inside the interval between 91.7 and 98.4 %. The average total annual rainfall value was equal to 507.7 ± 127.8 mm and was also used in the calculation of the total amount of water which was available for harvesting in Makhanda. Based on the 12-month standard precipitation index values, there were 6 hydrological droughts in Makana during the study period. The probability of using alternative potable water source by the Makana population was estimated at 59.5 %, while there was a 28.8 % probability that a Makana household would have a RWH system installed. Using the 2020 rainwater harvesting system prices and involvement of the households' occupants in the system installation, the total cost of providing each Makana household with a rainwater harvesting system was estimated at 44.493 million ZAR (1 USD = 15-19 ZAR). The *total estimated volume of harvestable rainwater ranged from 17.2 to 48.6 m^3, with the first-flush trap decreasing the volume by 25.3 %. If a 2500 litres tank was installed at each household in Makana, then the harvested rainwater could sustain an average-sized household for 4.5 and 37 days, based on the levels of consumption.*

Keywords: *rainfall, safety, water capture, reservoir, rainfall index*

Abstrakt:
Štúdia sa snaží odhadnúť celkový ročný objem zberateľnej dažďovej vody v miestnej samospráve Makana. Mesačné modely zrážok boli analyzované pre obdobie 2000-2020. Mesačné zrážky sa nemenili s časom počas desiatich mesiacov v každom roku sledovaného obdobia (p-hodnoty sa pohybovali od 0,1941 do 0,9518). Mesačné zrážky sa vo februári časom zvyšovali (p-hodnota = 0,0497) a klesali s časom v apríli (p-hodnota = 0,0235) medzi rokmi 2000 a 2020. Skutočné hodnoty mesačných zrážok sa pohybovali od 0,0 do 218,4 mm. Úplnosť údajov o zrážkach sa pohybovala od 75 do 100 %, pričom ich spoľahlivosť bola v intervale 91,7 až 98,4 %. Priemerná hodnota úhrnu ročných zrážok bola 507,7 ± 127,8 mm a bola použitá aj pri výpočte celkového množstva vody, ktorá bola k dispozícii na zber v Makhande. Na základe 12-mesačných štandardných hodnôt zrážkového indexu bolo v Makane počas sledovaného obdobia 6 hydrologických období sucha. Pravdepodobnosť využívania alternatívneho zdroja pitnej vody obyvateľstvom Makana bola odhadnutá na 59,5 %, pričom pravdepodobnosť, že domácnosť v Makane bude mať nainštalovaný systém RWH, bola 28,8 %. Na základe cien systému na zachytávanie dažďovej vody z roku 2020 a zapojenia obyvateľov domácností do inštalácie systému sa celkové náklady na vybavenie každej domácnosti Makana systémom na zachytávanie dažďovej vody odhadli na 44,493 milióna ZAR (1 USD = 15 – 19 ZAR). Celkový odhadovaný objem zachytávanej dažďovej vody sa pohyboval od 17,2 do 48,6 m3, pričom lapač prvého splachu objem znížil o 25,3 %. Ak by bola v každej domácnosti v Makane nainštalovaná nádrž s objemom 2 500 litrov, potom by zozbieraná dažďová voda dokázala udržať domácnosť priemernej veľkosti na 4,5 a 37 dní, na základe úrovne spotreby.

Kľúčové slová: *zrážky, bezpečnosť, zachytávanie vody, nádrž, zrážkový index*

Introduction

Disaster impacts and complexity in South Africa

In the 21st century, the global ecosystem had entered the Age of Anthropocene where the fate of this global ecosystem has been heavily impacted by human action (Lewis and Maslin, 2015). Qualitative and quantitative nature of those impacts and changes they trigger in socio-ecological systems, are cumulative and many are irreversible in nature. Human development needs to take in account this irreversible nature of such human actions in the Age of Anthropocene. They must be understood in various levels of organisation (Madondo et al., 2023). Understanding various levels of complexity and the completeness of the disaster risk management (DRM) puzzle allow humanity to understand the nature of the human vulnerability to particular hazards, to develop and implement the required elements of adaptation and resilience approaches. Resilience will, to a large extent, be driven by the need to adapt to the ever-increasing number of disasters that have been caused by human action, and that are complex in nature and that thus have complex impacts on humanity. South Africa has been facing a multitude of concurrent disasters in recent years. Examples include the recent floods in the province of KwaZulu-Natal (Naidoo, 2022). There are also the ongoing pandemics of HIV/AIDS and tuberculosis, where South Africa is amongst the most impacted countries worldwide in terms of disease burden and the drug-resistant strain prevalence (NICD, 2021). Further to the DRM of the country, South Africa is prone to drought and fires, which can be manmade and natural in terms of hazard origin. In 2018, there were 5283 fires in informal settlements in South Africa, with the leading causes being the use of open flames and the undetermined causes (FPASA, 2018). Thus, communities In South Africa are impacted by manmade and natural disasters, which are triggered by multiple hazards at once. Therefore the DRM landscape in the country is complex.

This needs to be taken into consideration in protecting human wellbeing and maintaining access to basic public goods under such multi-hazard conditions. Drinking water provision to a disaster-impacted population is one such good or human need. Its delivery and provision are critical to protection of human wellbeing under normal circumstances and during DRM planning and execution. Changes in the provision of public goods can be impacted by changes in precipitation patterns around South Africa. Floods, fires and epidemics, mentioned in the previous paragraph, all have implications on the deployment of resources which the South African DRM system must utilise to manage and mitigate the disaster hazards and their impacts on the South African population. One such resources is the water utilisation (Galvin and Masombuka, 2020). Water is scarce in South Africa and the multi-hazard DRM space in parts of the country requires careful consideration about what volumes are available or can be used for mitigating with disaster hazard. Madondo et al. (2023) showed that the fire disaster management can be in competition with other water uses in the drought-stricken parts of South Africa, e.g. the Eastern Cape Province.

Makana Local Municipality is located in the Eastern Cape Province of South Africa (designated as Makana in further text of the article). Water outages and water quality problems, in relation to municipal drinking water, and droughts have been common in the area (Nhokodi et al., 2023a,b). Therefore it comes as no surprise that the local population is looking for the use of alternative water sources to meet domestic demand (Iheanetu and Tandlich, 2022). Looking for alternative water supply and taking the Makana population’s challenges into account, there is potential for the alternative water sources to trigger secondary disasters (outbreaks of waterborne and diarrhoeal diseases upon consumption of such water). This is important to increase water security in Makana. There is also the possibility for the use of alternative water sources for potable uses to exacerbate the impact of other/existing disasters hazards, e.g. the use of untreated water for drinking can increase vulnerability of the Makana population in situation of a concurrent disasters…a site of a recent urban dwelling fire. One such alternative source is rainwater harvesting (RWH). RWH can be broadly defined as the 'collection and storage of rainwater for domestic purposes and has been done through the collection of rainwater from rooftops, courtyards, and subsequently storing the harvested rainwater in tanks' (Fisher-Jeffes et al., 2017; Angala et al., 2019).

Under the drinking water provision in Makana and South Africa, RWH can become a risk enhancer or a tool for water scarcity/drought adaptation, depending on the implementation of RWH. Use of RWH must be integrated into the complex DRM landscape in a disaster area (Hochrainer-Stigler et al., 2023), e.g. such as Makana. However, the method has several advantages in comparison to other potable water delivery methods. Firstly, the RWH systems can be deployed in a decentralised manner and there limited to no need for reticulation at the point of consumption (MIT, undated). RWH can also be implemented quickly during sudden need for surge capacity in drinking water needs (Kanno et al., 2021). Local conditions and rainfall patterns determine the potential uses of the harvested rainwater in a disaster-prone area. This is supported by findings of Fisher-Jeffes et al. (2017) studied the potential use of the rainwater harvesting to manage the stormwater surges. Results of that study indicated that installation of the RWH systems for management of stormwater would only be possible in the high-income households. During the COVID19, Kanno et al. (2021) studied the potential to deploy and install rainwater harvesting systems for the provision of drinking water during an emergency or public-health disaster and found it sufficient for hygiene purposes. Sudden installation of the RWH system can lead to increased provision of drinking water and thus supply of an essential resources to the disaster-affected population. This means an increase in water security of said population.

Facing the multiple disaster hazards of drought, water scarcity and problems in drinking water delivery (Iheanetu et al., 2022; Nhokodi et al., 2023a,b), Makana population must be provided/equipped with the necessary tools to cope with disaster impacts. The DRM system must provide solutions that are tailored to local possibilities and DRM conditions. There is an urgent and ongoing need for adaptation strategies to be put in place to provide alternative sources of drinking water at the household level in Makana. The current article is a continuation of the recent research on the subject by members of the author team (Iheanetu and Tandlich, 2022; Nhokodi et al., 2023a,b). Adaptation to drought and other disaster hazards is possible due to the installation, operation, monitoring, and repair of the RWH systems. This solution is environmentally-friendly and compatible with climate change adaptation, e.g. as shown in recent experiences from Brazil (de Sá Silve et al., 2022). Therefore RWH is suitable for application in the drinking water supply in the Age of Anthropocene. The collected and stored rainwater can be used to supplement or maintain supply of drinking water during a municipal outage. Therefore the RWH systems, if implemented in line with local conditions, can serve and contribute to the development a disaster resilient infrastructure for water supply in Makana (Nhokodi et al., 2023b). To achieve that study aims in this context, the authors seek to analyse the rainfall pattern in Makhanda/Grahamstown area of Makana between January 2000 and December 2020 (designated as 2000-2020 period/data in further text). Using the rainfall data and models from literature, the authors will estimate of the rainwater harvested volume under two scenarios. Firstly, the RWH system would be installed in a middle-to-upper-income suburb in the Makhanda/Grahamstown area of Makana (designated as Makhanda in further text of the article). Secondly, the harvesting would occur under a hypothetical scenario where the RWH is installed in a low-income neighbourhood in Makhanda. The RDP house is built or has been built since 1994 as part of the South African government to provide housing to previously disadvantaged parts of the population of the country (Weaver et al., 2017). As such, the house design is standard and widespread across South Africa. These two examples will provide a range of roof catchment areas and volumes that can be harvested at the household level for the alternative water supply in Makhanda.

Hydrological drought and scenarios of the RWH application in Makana

The 12-month standard precipitation index (SPI) was originally defined by McKee et al. (1993, 1995). It has been used to characterise hydrological drought levels, i.e. drought when the water level in streams and other water bodies are below normal (e.g. WMO, 2012). The SPI values, in combination of the existing challenges of water service delivery (Weaver et al., 2017), should provide an understanding about the water management conditions under which the RWH systems would be deployed in Makana. Hydrological drought would contribute to primary water scarcity by reducing the available volume of raw water. It could also provide a reasonable explanation for any drinking water supply interruptions to the Makana population. In any deployment of the RWH systems, the extent of this effects would need to be balanced against other challenges that Makana local government might face. The challenges in question would include non-collection of revenue for drinking water supply from Makana residents and technological/human-resource capacity challenges in the water sector in Makana (Weaver et al., 2017). Local conditions and the nature of the water supply solutions must also be considered. Hamer et al. (2018) reported that only 13 % of low-income settlement inhabitants of Makana had RWH at the dwellings. Rain water tanks are common place at public/government and types of buildings around Makhanda (authors' observations in the study area result in the estimate rate around 80 %). At the same time, Nhokodi et al. (2023b) proposed a strategy how the supply and treatment of drinking water could be improved, e.g. by providing a container treatment and testing solutions close to drinking water consumption points in Makana. Given this and the low-cost and the possibility of rapid deployment, RWH could play be used as a viable alternative drinking water source sin Makana. This could facilitate the improvement of water security of the Makana population.

Any deployment of the RWH systems needs to be integrated into the existing drinking water supply to the Makana population. There are two main systems which supply 12 megalitres/day of drinking water to the Makhanda population. The first system is the Kariega system which is owned by Makana and operated by the Amatola Water Board/MBB Consulting contractors (Rhodes University, 2016; Weaver et al., 2017). This water supply system is mainly used by the western side of Makhanda, i.e. the middle-to-upper-income neighbourhoods. This system supplies 9 megalitres of raw water for drinking water production per day. At the same time, the eastern side of Makhanda, which has historically been the low-income area of residence, is supplied by the Orange-Fish River-Interbasin transfer scheme (Rhodes University, 2016; Weaver et al., 2017). This water supply system is owned and operated by the South African National Department of Water and Sanitation, and it supplies about 3 megalitres/day of raw water for treatment into drinking water for the eastern side of Makhanda (Weaver et al., 2017). The combination and interlinking of the two systems are the most recent version of a water supply system with long history of development and adaptation (Mullins, 2011). The development of new elements and their addition to the Makana drinking water supply system over the last two centuries, and especially since the end of apartheid, indicate the Makana water supply is adaptive in nature. Therefore, RWH can be added to this system based on the existing and long-term adaptive nature of the water supply system in Makana. The DRM settings and policy environment for the RWH deployment must be adaptive as well. Integration of the rainfall data analysis and the SPI data in the study area would then be the basis for bounding the system of analysis in this article (Weaver et al., 2017). The bounding means here that the RWH implementation and deployment as part of DRM in Makana would need to be analysed in terms of existing water supply and the potential challenges that might arise in wider implementation In this way, RWH as part of the water supply system in Makana can be understood and its maximising of its deployment can be maximised. Water security of the Makana population can only be achieved if all modes and mechanisms of water delivery are coordinated. RWH will be seen in this context in the current paper.

The working hypothesis and the specific aims of the study

The working hypothesis of the current study is that all domestic uses of the average size household in Makana can be met by harvesting and storing rainwater from the roof of the family's dwelling. The best estimate can be obtained from the average monthly rainfall which was measured in Makhanda by the South African Weather Service (the official meteorological agency of the South African government). The completeness and reliability of the rainfall data must be assessed to ensure that estimates from all models form a realistic basis for DRM planning and improvement in the water supply resilience of the Makana population. In addition, the likelihood of the usage of alternative water sources by a Makana household was estimated based on the water-related complaints of the Makana population. That was evaluated from the online MobiSAM platform (see mobisam.net for details: website accessed on 19th December 2023) and the rate of planned water outages in Makana. The current article and its results, the bounding of the current study will form a potential way to mitigate the impacts of the drought and water scarcity, as well as the multi-hazard DRM landscape of Makana, on the impacted population. The results could also contribute to the sustainability of the drinking water provision and supply to the Makana population. That in turn could facilitate increase water security and improve disaster resilience in Makana and for the Makana population.

Materials and Methods

Analysis of rainfall data for Makhanda

The monthly rainfall data for Makhanda were obtained via email from the Gqeberha/Port Elizabeth Office of the South African Weather Service for the 2000-2020 time period. This period is sufficient to analyse the Standard Precipitation Index in a given area (WMO, 2012). The total monthly rainfall volumes were extracted and tabulated. Statistical analysis was performed to establish several aspects of the rainfall patterns in Makhanda. Firstly, the Kruskal-Wallis analysis of variance by ranks at 5 % level of significance was used to see whether there were statistically significant differences between the monthly rainfall volumes between 2000 and 2020. After that, the Mann-Kendall test at 5 % level of significance was used to see whether the monthly rainfall volumes per January-December were systematically increasing, decreasing or whether they remained constant between 2000 and 2020. All analyses were performed using the Past 3.0 statistical software package (Hammer et al., 2001). After this step, years with the minimum monthly rainfall and the maximum monthly rainfall for January, February,..., December were identified and tabulated. Next, the completeness and reliability of the rainfall data were estimated and evaluated. Completeness of the monthly rainfall data in a given calendar year (X) were calculated as shown in Equation (1)

$$X = 100 \times \frac{Actual\ number\ (measured\ rainfall\ in\ a\ year)}{Total\ number\ (measured\ rainfall\ in\ a\ year)} = 100 \times \frac{Actual\ number\ (measured\ rainfall\ in\ a\ year)}{12} \quad (1)$$

In Equation (1), *Actual number (measured rainfall in a year)* stands for the number of months in a given year where the reliable rainfall data were recorded and reported by the South African Weather Service. At the same time, *Total number (measured rainfall in a year)* stands for the number of months in a given calendar year, i.e. 12. The *X* value from Equation (1) is equal to the frequency-based abundance/probability of availability of the monthly rainfall data from the South African Weather Service (Kampová and Loveček, 2020a). It is a dimensionless parameter, which is reported as percentages by applying the conversion factor of 100.

Reliability of the rainfall data from the South African Weather Service were calculated as the average probability that in the rainfall data would be measured on a given day and that this would provide a reliable foundation for the monthly rainfall values. This parameter was designated as *Y* and it was calculated as shown in Equation (2).

$$Y = 100 \times \left(1 - \frac{No\ value\ days\ number\ (given\ year)}{The\ average\ total\ number\ of\ days\ in\ a\ year}\right) = 100 \times \left(1 - \frac{No\ value\ days\ number\ (given\ year)}{365.43}\right) \quad (2)$$

In Equation (2), *Y* is the percentage of all the Makhanda daily rainfall values that were measured in a given calendar year. The numerator on the right-hand side contains the number of days in given year where a rainfall reading was missing for Makhanda (*No value days number (given year)*). The denominator on the right-hand side was equal to the average number of days in a calendar year between 2000 and 2020 (designated as *the average number of days in a year* or 365.43). The South African Weather Service dataset contained two measures of data quality. If the data were not available for a given day or the missing on that day, then such data point was designated as *** in the provided dataset. If a monthly value was unreliable, then that monthly rainfall was designated as = in the provided dataset. The values for *Actual number (measured rainfall in a year)* in Equation (1) were equal to number of values in a given year with the exception of the = term. The *No value days number (given year)* values were equal to the *** data from the South African Weather Service dataset.

The number of no-rain days in a given calendar year (designated as *DWR* in further text of the article) was calculated as the number of days where the value of precipitation was reported as 0. Practically, a 0 here are all days when the rainfall recorded in Makhanda was below 0.1 mm. Next, the rainfall data for the study area were used to calculate the total annual rainfall in Makhanda (*TAR*). This parameter is defined in Equation (3) below.

$$TAR = \sum_{1}^{12} Monthly\ rainfall \quad (3)$$

In Equation (3), the *Monthly rainfall* is a value for the monthly precipitation in a given month of a given calendar year between 2000 and 2020. Any temporal trend in the values of *X*, *Y*, *DWR* and *TAR* were investigated using the Mann-Kendall test at 5 % level of significance, in a similar fashion as outlined for the monthly rainfall data.

Hydrological drought and likelihood of deployment of alternative water sources in Makana

The SPI values were calculated manually using MS Excel (Microsoft Inc., Johannesburg, South Africa) and the parameter definitions of McKee et al. (1993, 1995). Description of the practical significance of the 12-month SPI (as near normal, moderately-to-extremely west or dry conditions in Makana) was evaluated based on the guidelines of the European Commission (EC, 2020). Hydrological drought will be detected, if the SPI value becomes negative, it keeps decreasing and eventually drops to values of -1.0 or lower (WMO, 2012). If hydrological drought sets in inside Makana, then the Municipality could have justified reason to not provide a sustainable water supply to the Makana population. This would be based on the fact that as raw water supply for production of drinking water and the related water treatment would be interrupted. Result of that set of circumstances would in turn be that no drinking water is likely to be supplied to Makana population. Interruption of drinking water supply would be a cascading effect of the hydrological drought. If the hydrological drought was, however, not underway and there was an interruption of the municipal drinking water supply to the households in Makana, then that would be the result of technical, human resources or other challenges that might prevent Makana from carrying out its water authority mandate (Weaver et al., 2017). This would be indicated by complaints from residents and the reporting of the water supply outages or infrastructure problems by them. Such complaints would not be resolved by Makana. To investigate the likelihood or the frequency-based probability of this occurring, the SPI values were interpreted along with the reporting of the water service issues on MobiSAM (see mobisam.net for details; website accessed on 31st December 2023). The likelihood also included the consideration of the planned water supply outages in Makana due to drought and water scarcity.

The number of complaints or issues, that had been logged on the MobiSAM platform between 2013 and 2023, was analysed to identify the total number of water-related queries. The number of open and/or unresolved items was related to the total number of water-related items and used to calculate the probability of the unresolved water-related issues, that have been faced by Makana residents between 2013 and 2023, i.e. (*PUWI*). (*PUWI*) can be calculated as shown in Equation (4).

$$PUWI = 100 \times \left(\frac{open\ items + assigned\ items\ water\ on\ MobiSAM}{The\ total\ number\ of\ water\ items\ logged\ on\ MobiSAM}\right) \qquad (4)$$

In Equation (4), the numerator on the right-hand side stands for the number of the water-related issues that had been reported by the Makana residents to their local government, but which remained unresolved. The denominator in Equation (4) stands for the total number of the water-related problems that have been reported by the residents to Makana local government between 2013 and 2023. Since 2015, Makhanda has experienced various series of water cuts, i.e. the drinking water supply is interrupted due to primary water scarcity or due to infrastructure supply problems/secondary water scarcity (Iheanetu and Tandlich, 2022; Nhokodi et al., 2023a,b). These water cuts were in place in 2020 and were only really suspended for the period of the harshest COVID19 lockdowns (Tandlich, 2020). The water supply interruptions generally follow a pattern of 1 day of water supply of the municipal drinking water by Makana to its residents, and one day of interruptions. This can be extended to two days of cuts and one day of supply (the authors' observations from the study site). This information was taken into account to calculate the probability of water supply interruptions in Makhanda (*PWSI*), as the arithmetic average of the two numbers.

Estimation of the RWH installation rate and volumes of rainwater for harvesting in Makhanda

Rate of the RWH installation or use in Makhanda was estimated using literature data and the principles of Bayesian probability based on the authors' experiences in the study area. The rate of RWH installation and use at the household level in Makhanda (*RRIM*) can be calculated using the data of Weaver et al. (2017) and Hamer et al. (2018), along with the Bayesian estimates by the authors. The resulting *RRIM* is defined in Equation (5).

$$RRIM = WGWS \times BP + EGWS \times HRWHR \quad (5)$$

In Equation (5), *WGWS* is the percentage of the Makhanda population which is supplied by the Kariega system. *BP* stands for the Bayesian statistical estimate about the rate of the RWH installation at household level in the Western part of Makhanda, i.e. the middle-to-upper-income suburbs. *EGWS* is the percentage of the Makhanda population which is supplied by the Orange-Fish-River Inter-basin transfer system. Finally, *HRWHR* stands for the rate of RWH installations in the low-income suburb in the Eastern part of Makhanda, as reported by Hamer et al. (2018).

The roof area of the last author's house was calculated based on measurements of the dimensions of the back side of the house and the one of the sides facing the streets. The details in the rainwater harvesting system and the roof catchment are shown in Figure 1. That roof area was the catchment that can be exploited to harvest the rainwater on an annual basis. The average *TAR* values for Makhanda were used to estimate the total rainwater volume that is available for possible harvesting (*TVRH*) in the middle-to-upper-income neighbourhood in Makana. The method of Hari (2019) and Kanno et al. (2021) was modified used to estimate the *TVRH* values. The total rainfall volume would be calculated as shown in Equation (6).

$$TVRH = 0.001 \times 0.85 \times A_{\text{Roof}} \times \ TAR_{\text{average}} \quad (6)$$

In Equation (6), *TVRH* is reported in m^3 and A_{Roof} is the size of the roof catchment area (m^2). The roof tiles at the last author's house were made from asbestos and so the runoff coefficient was equal to 0.85 (Hari, 2019; Kanno et al., 2021), as shown in Equation (6). The conversion factor of 0.001 is used to convert the *TAR* values to m. Two correction factors were implemented in the *TVRH* model. Firstly, values of *X* and *Y* were taken into account to reflect the uncertainty of the monthly and yearly rainfall data for Makhanda and its impact on the *TVRH* values. The *X* and *Y* values were averaged, and the correction factor was introduced into the model from Equation (6) to prevent underestimation of *TVRH*. That correction factor was equal to 0.94.

Secondly, the first-flush effect on the precipitation that would be available for rainwater harvesting was calculated. This parameter is designated as *FFE* in further text of the article. The *FFE* values were estimated based on the size of the first-flush trap (see Figure 1 below). As the trap is a cylinder and its dimension were measured, its volume was estimated at 13.1 litres. Now, this number might be decreased as the effective first-flush trap volume, if debris such as leaves would fall into the first flush trap. To assess this effect, the rainfall was measured at the last author's house during five rainfall occasions. A rain gauge was purchased from Buco (Makhanda, South Africa) and calibrated by filling it up with water and weighing (a modified technique of Madikizela et al., 2022). The rainfall was measured on five separate occasions during rainfall events which lasted from 8 to 36 hours. The measured rainfall ranged from 0.8 to 4.2 mm, and the first-flush trap was drained after the completion of each event to measure the volume of water in the first-flush trap. An F1976 portable electronic scale (Model: 14191-744E) was purchased from Takealot and calibration weights of 1, 5 and 10 kg were purchased from SCALETEC (Durban, South Africa).

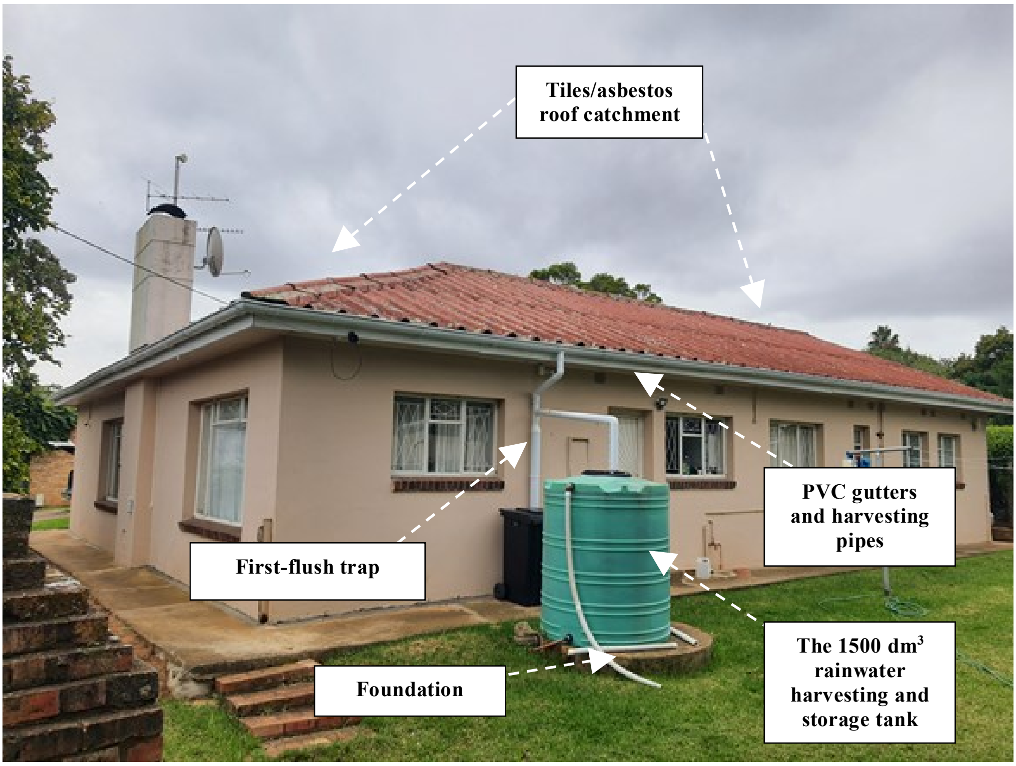

Figure 1. *Representation of the roof catchment and the harvesting system for rainwater collection in the Makhanda area of Makana Local Municipality. This catchment represents the roof area for harvesting of rainwater in the middle-to-upper-income neighbourhood in Makana.*

A plastic bag was hung on the scale and weighed. The same was done for an empty bucket and the calibrated weights or water could be tared, and be weighed accurately under the field conditions. Then the scale was calibrated using the calibrated weights of 1 and 10 kg, with 5 kg weight being used as an accuracy reference standard. The first-flush trap was emptied into the bucket and the water was weighed (m_i). The ambient temperature on the day was recorded and used to obtain the density of water (ρ_i; see https://www.vip-ltd.co.uk/Expansion/Density_Of_Water_Tables.pdf for details; website last accessed on 2nd January 2024). The procedure was repeated on all 5 occasions and the *FFE* value was calculated as shown in Equation (7).

$$FFE = 0.5 \times \left(13.1 + \sum_1^5 \frac{m_i}{\rho_i}\right) = 0.5 \times (13.1 + 9.2) = 11.2\ litres = 0.0112\ m^3 \quad (7)$$

The *FFE* value for further modelling was equal and rounded off to 11.2 litres. The *FFE* value must be converted into mm of precipitation and the correction must be made for the 0.1 mm of precipitation not accounted for in the South African Weather Service data. In other words, 0.1 mm of precipitation was lumped into the *FFE* value. The first-flush trap had a circumference of 360 mm, and its PVC pipe was 3 mm thick. As the outer wall and the inside of the PVC pipe formed two concentric circles, the cross-sectional area of the first-flush trap was equal to 9261 mm^2 (area of the inside circle). The *FFE* value was equal to 11.2 litres or 11200 mm^3, and so the effective rainfall trapped in the first-flush trap was equal to 1.3 mm. That volume was constant per rainfall event, as it was independent on the precipitation during the five tested events. The *FFE* value per annum in mm of rainfall or FFE_{annum} is defined in Equation (8).

$$FFE_{Annum} = 1.3 \times (365.43 - DWR) \quad (8)$$

Practically, two situations can be expected. Firstly, a house/roof catchment will be coupled with the first-flush trap. Secondly, such a catchment might not be coupled with a first-flush trap. Corrections of the harvestable water will be applied to account for both cases.

The next task in the study was to measure the size of the roof catchment in the last author's house. The roof catchment was located on the back of the house, as that is where the rainwater harvesting system was located (see Figure 1 for details). The schematic representation of the roof catchment is shown in Figure 2 below. A_{Roof} was calculated as the sum of the area of two right-angled parallelograms and one right-angled triangle. The A_{Roof} for the middle-to-upper-income neighbourhood was equal to 119.8 m^2 as a result. The *TVRH* model from Equation (6) was modified for the calculations in Makhanda as shown in Equations (9)-(12).

$$TVRH = 0.001 \times 0.85 \times 0.94 \times 119.8 \times [TAR_{average} - 1.3 \times (365.43 - DWR)] \quad (9)$$

$$TVRH = 0.0957 \times [TAR_{average} - 1.3 \times (365.43 - DWR)] \quad (10)$$

$$TVRH = 0.001 \times 0.85 \times 0.94 \times 119.8 \times TAR_{\text{average}} \quad (11)$$

$$TVRH = 0.0957 \times TAR_{\text{average}} \quad (12)$$

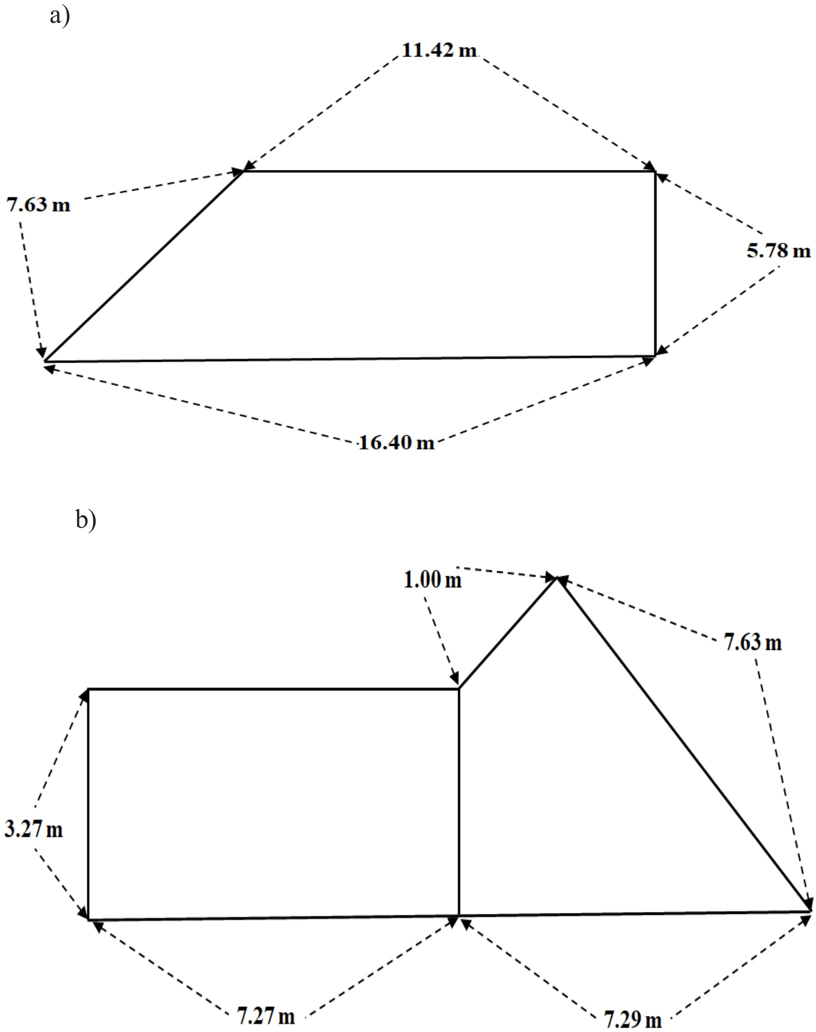

Figure 2. *Schematic representation of the roof catchment on the back of the last author's house (a) and the side of the last author's house (b) in the Makhanda area of Makana Local Municipality.*

Equations (9) and (10) are the final model equations to estimate the total volume of rainwater that can be harvested in a household from a middle-to-upper-income neighbourhood in Makhanda, where a first-flush trap is installed. Equations (11) and (12) have the same purpose, but no first-flush trap would be installed at that house. For practical model estimates, Equations (10) and (12) will be applied in the Results and Discussion section.

For the low-income neighbourhood, the standardised design an RDP house will result in a standard roof catchment area. Description of some of the RDP designs were recently reported upon by Mabuya and Scholes (2020).

In these dwellings, the first-flush traps are generally not installed. The floor areas ranged from 36 to 40 m^2 and the roof material was generally either asbestos (runoff coefficient of 0.85) or corrugated iron (runoff coefficient of 0.95). Asbestos is in this article also seen as including any clay or ceramic materials that are still used as roofing across the Eastern Cape. The runoff coefficient in Equation (6) was therefore replaced with 0.90 for the low-income neighbourhood in Makhanda. For modelling estimates and given the information in this paragraph, Equation (11) formed the basis for the calculation the volume of rainwater which can be harvested per annum in the low-income neighbourhood in Makhanda. The only modification was in the A_{Roof} value. This will be estimated using the following procedure. Data from the RDP study by Mabuya and Scholes (2020) shows that the average floor area of an RDP house is 38 m^2 in South Africa. The roof area closely follows this area, but the roofing material extends an extra 20 cm on two of the four sides of the house (authors' observations from Makhanda). At the same time, the roof slants at a small angle, namely about 10-15 °. Therefore the A_{Roof} value for the low-income neighbourhood household was estimated to be equal to 40 m^2 for modelling estimates. This can then be used to obtain a modified version of Equation (11) and (12), namely Equations (13) and (14).

$$TVRH = 0.001 \times 0.90 \times 0.94 \times 40.0 \times TAR_{\mathrm{average}} \quad (13)$$

$$TVRH = 0.0338 \times TAR_{\mathrm{average}} \quad (14)$$

Various volumes per capita and per specific use have been published in the literature. Populations access to water is essential and volumes per activity, e.g. hand-washing or cooking will depend on the socio-economic, cultural, and other factors. In this study, the Sphere handbook guidelines for the water provision will be used (Sphere, 2018, Appendix 3, page 145). It is clear that Sphere Handbook is primarily applied to humanitarian assistance, and not life in a democratic society which is politically stable. However, the argument is made here by the authors that the Sphere Handbook contains the minimum standard volumes of drinking water per domestic use or human activity that ensure maintenance of human wellbeing. As such, the volumes can be used as a guideline for the use of rainwater under alternative water supply conditions in Makhanda. The use of minimum volumes in the modelling estimates can provide an indication about the maximum period of time that the RWH can be used to supply the Makana population with drinking water. These volumes will be as follows per person per day in Makhanda (Sphere, 2018, Appendix 3, page 145): 2.5 litres for drinking and food consumption, 2.0 litres for personal hygiene besides flushing of toilets, 3.0 litres for cooking meals and 10 litres for flushing toilets. Based on the data by Galvin and Masombuka (2020), 3.0 litres will be assumed for taking medication and performing hygiene related to HIV/AIDS patients in a household. The daily expected consumption of drinking water from RWH as an alternative source will be assumed to range from 17.5 to 20 litres per person per day. Use of the Sphere standards for water supply as the minimum standards leads to the linking between water security, its minimum volumetric requirements. It also should be seen as a tool to provide information and analytical tools that can ensure a resilient provision of service to the Makana population which is conducive to the maintenance of disaster-resilient population. The itemised breakdown of the minimum daily volume of water, should not be seen as consideration of Makana population of refugees or people in distress. It is rather the view that the Sphere volumes of water per specific use can be seen as optimised way to ration and use most effectively water resources in a drought-stricken area.

Results and Discussion

Analysis of rainfall data for Makhanda

The monthly rainfall data for Makhanda are shown in Table 1. Results of the Kruskal-Wallis analysis of variance by ranks, at 5 % level of significance, showed that the monthly rainfall varied in Makhanda across a given calendar year and across the years in the study period (p-value = 0.00005). The Mann-Kendall test at 5 % level of significance results and detected trends are summarised in Table 2. From that data, it can be seen that the monthly rainfall did not show any systematic trend, for all but two months out of a given calendar year, during the study period (p-values ranged from 0.1941 to 0.9518). It increased with time for February (p-value = 0.0497) and decreased with time in April (p-value = 0.0235) between 2000 and 2020. The minimum monthly rainfall was equal to 0.0 mm in March 2001, May-July 2014 and August 2019. The maximum monthly rainfall was equal to 218.4 mm in August 2006. The median monthly rainfall in Makhanda was equal to 40.5 mm. This is comparable to or lower than the monthly rainfall range reported for the Turksvybult area in the Limpopo Province in northern South Africa (Tadesse and Dinka, 2023). In that study, the reported rainfall range was between 0.0 to 1555.7 mm with a median value of 113.8 mm (Tadesse and Dinka, 2023). The current data are slightly lower or comparable to ones reported for the 1900-2019 period for the Makhanda area by Kibi (2021, Table 12, page 72). Different data sources could provide an explanation here.

Completeness and reliability of the rainfall data, along with the *TAR* values, are shown in Table 3. As it can be seen, completeness of the rainfall data ranged from 75 to 100 % and was comparable to the expected completeness of rainfall monthly data (WHO, 2012). Therefore the monthly rainfall data for Makhanda can be seen as falling within acceptable completeness range for precipitation data, as basis for further calculations.

The reliability of the Makhanda rainfall data ranged from the minimum of 91.7 % in 2020 to a maximum of 98.4 % in 2000. Both X and Y showed no systematic trend for the study period with the Mann-Kendall test at 5 % level of significance and p-values of 0.3749 and 0.2061, respectively. A concern was the increased number days with missing measurements in 2020, i.e. from 6-13 for the 2000-2019 period to 31 in 2020. The COVID19 lockdowns, the related mobility restriction and the likely changes in operation/personnel monitoring of the rainfall gauges could provide an explanation here. The average values can be calculated for *X* and *Y*, and these can be used in the estimation of the water quantity which can be available for RWH in Makhanda. The average *X* value was equal to 90.8 ± 8.9 % and the average *Y* value was equal to 97.2 ± 1.5 %. These two values were averaged and the lumped average of 94.0 % was used in the model estimates of the rainwater that could be harvested in Makhanda (see below).

Table 1. *The Makhanda monthly rainfall from January 2000 until December 2020, as provided by the South African Weather Service.*

Calendar year	Calendar month precipitation											
	Jan (mm)	Feb (mm)	Mar (mm)	Apr (mm)	May (mm)	Jun (mm)	Jul (mm)	Aug (mm)	Sep (mm)	Oct (mm)	Nov (mm)	Dec (mm)
2000	60.8	20.8	115.8	61.4	7.8	5.0	0.2	3.2	55.8	82.8	139.0	12.6
2001	63.2	18.0	0.0	73.6	9.0	19.4	43.0	48.0	62.9	19.0	94.8	38.7
2002	45.0	15.8	21.4	68.8	33.6	33.8	86.8	164.2	122.0	11.0	24.6	39.2
2003	16.8	70.6	68.2	35.6	58.4	7.2	5.6	18.6	8.8	55.2	27.4	14.8
2004	27.6	38.6	15.6	60.4	16.2	8.2	23.4	28.4	107.8	44.6	12.0	82.8
2005	38.4	86.2	40.0	74.6	25.0	13.6	7.8	19.4	11.6	24.2	136.6	5.4
2006	59.6	67.4	29.8	35.2	85.4	24.4	10.4	218.4	34.4	66.4	23.2	51.8
2007	26.8	29.0	102.4	45.0	34.0	34.8	13.0	18.6	4.2	31.6	31.4	70.6
2008	60.6	28.6	49.8	29.8	12.6	17.0	0.8	25.2	12.2	31.8	46.6	33.8
2009	19.8	125.8	12.0	13.2	10.2	28.2	45.2	8.0	17.0	95.0	29.2	14.2
2010	51.6	32.0	13.0	48.4	3.4	70.4	8.8	14.0	13.4	115.0	25.6	77.0
2011	34.4	22.0	52.6	51.8	94.2	134.0	122.0	28.2	1.8	60.8	105.8	30.0
2012	16.6	68.8	70.4	27.2	8.6	35.8	75.4	26.4	19.2	212.4	14.8	47.8
2013	23.0	36.4	65.6	26.6	33.2	11.6	12.2	26.6	0.8	121.2	79.6	40.2
2014	25.0	86.6	27.2	119.0	0.0	0.0	0.0	19.2	59.2	53.0	111.2	49.2
2015	88,6	59.2	69.8	96.8	4.4	92.4	119.6	31.8	40.8	15.4	79.8	2.8
2016	41.2	53.0	53.2	26.0	14.0	11.6	73.6	16.4	17.4	9.8	43.0	22.2
2017	68.0	80.2	28.6	21.8	29.0	0.8	3.0	60.2	37.2	77.2	70.0	28.4
2018	50.0	96.2	56.0	30.4	20.0	7.2	14.2	49.6	56.8	33.2	42.8	3.0
2019	25.0	20.2	88.0	5.8	23.4	9.6	12.2	0.0	18,8	13	4.6	11.6
2020	94.2	139.0	66.4	34.8	7.4	9.4	4.2	13.6	9.0	69.6	37.8	65.4[a]

This record was incomplete and so alternative and public data was used instead as average from the reference of the local newspaper (see https://grocotts.ru.ac.za/2021/01/04/how-much-was-that/ for details; website accessed on 30th December 2023). This source is known to be reliable for reporting of water issues in Makhanda and the extracted values are considered reliable for by the authors for monthly rainfall in the study area.

Table 2. *Results of the Mann-Kendall test and the calculations of completeness and reliability of the rainfall data for the Makhanda from January 2000 until December 2020, as provided by the South African Weather Service.*

The *TAR* values were not showing any systematic trend during the study period (Mann-Kendall test at 5 % with p-value = 0.6506). The average *TAR* value was equal to 507.7 ± 127.8 mm and was also used in the calculation of the total amount of rainwater which was available for harvesting in Makhanda. The *TAR* values were below the world average annual precipitation of 1180 mm (estimated as an equal-weight average of the World Bank data at https://data.worldbank.org/indicator/AG.LND.PRCP.MM; website accessed on 2nd January 2023). It has to be said, however, the World Bank dataset was incomplete for multiple countries and so the value of 1180 mm should be regarded as an approximate estimation. The *DWR* values did not show any systematic trends between 2000 and

2020, as the Mann-Kendall test at 5 % level of significance had a *p*-value of 0.4493. The mean *DWR* value stood at 267 ± 15 days. Therefore any rainwater can only harvested be harvested 26.9 % of days in a given calendar year, and any such harvested rainwater will have to be stored for further use in between rainfall events. This in turn would require focus on rainwater storage infrastructure, e.g. tanks, across Makhanda.

Month	Mann-Kendall test results per month in all years	Year of month with minimum rainfall (actual rainfall value in that month, mm)	Year of month with maximum rainfall (actual rainfall value in that month, mm)
January	No significant trend, *p*-value = 0.8562	2012 (16.6)	2020 (94.2)
February	Significantly increasing trend, *p*-value = 0.0497	2002 (15.8)	2020 (139.0)
March	No significant trend, *p*-value = 0.1941	2001 (0.0)	2000 (115.8)
April	Significantly decreasing trend, *p*-value = 0.0235	2009 (13.2)	2014 (119.0)
May	No significant trend, *p*-value = 0.4503	2014 (0.0)	2011 (94.2)
June	No significant trend, *p*-value = 0.8324	2014 (0.0)	2011 (134.0)
July	No significant trend, *p*-value = 0.9518	2014 (0.0)	2015 (119.6)
August	No significant trend, *p*-value = 0.6723	2019 (0.0)	2006 (218.4)
September	No significant trend, *p*-value = 0.5259	2013 (0.8)	2004 (107.8)
October	No significant trend, *p*-value = 0.7858	2016 (9.8)	2012 (212.4)
November	No significant trend, *p*-value = 0.6946	2019 (4.6)	2000 (139.0)
December	No significant trend, *p*-value = 0.5661	2020 (2.0)	2004 (82.8)

Table 3. *The total annual precipitation in the Makhanda as per the South African Weather Service data.*

Calendar year	*X*	*Y*	*DWR* (*dimensionless*)	*TAR* (*mm*)
2000	100	98.4	268	565.2
2001	83.3	96.4	268	489.6
2002	91.7	97.3	256	666.2
2003	91.7	97.5	268	387.2
2004	75.0	97.3	267	465.6
2005	83.3	96.4	280	482.8
2006	100	98.1	232	706.4
2007	100	98.1	261	441.4
2008	91.7	98.1	273	348.8
2009	100	98.1	272	417.8
2010	83.3	97.5	258	472.6
2011	100	98.1	247	737.6
2012	100	98.4	245	623.4
2013	100	98.1	271	477.0
2014	91.7	97.8	296	549.6
2015	91.7	97.3	261	701.4
2016	83.3	97.5	281	381.4
2017	91.7	97.5	264	504.4
2018	75.0	95.6	283	459.4
2019	75.0	96.4	294	232.2
2020	91.7	91.8	255[a]	550.8[a]

This record was incomplete and so alternative and public data was used instead as average from the reference of the local newspaper (see https://grocotts.ru.ac.za/2021/01/04/how-much-was-that/ for details;

website accessed on 30th December 2023). This source is known to be reliable for reporting of water issues in Makhanda and the extracted values are considered reliable for by the authors for monthly rainfall in the study area.

Hydrological drought and likelihood of deployment of alternative water sources in Makana

The standard precipitation index (SPI) for Makhanda as a function of time is shown in Figure 3. The 2000-2020 SPI values indicated that 66.8 % of months had near normal rainfall in Makhanda, 10.0 % were moderately wet, 7.5 % of all months were very wet and 1.2 % were extremely wet. On the other hand, 9.5 % were moderately wet, 1.7 % of all months were extremely dry and 3.3 % of all months were severely dry. The SPI on a 12-month scale is expected to contain mostly near normal values (WMO, 2012). Negative SPI values were observed between March and June 2001, as well as between November in the same year and April 2002. However, the values did not decrease with time and it did not reach values below -1.0. Values of SPI became negative again in September 2003, and hydrological drought was encountered between February and August 2004 (see Figure 3 for details). Another hydrological drought was detected between August 2007 and January 2009. Near normal but negative SPI values continued until about April 2011. Further to hydrological drought occurrence, another one was faced by Makana between June and December 2016, and from February to August 2017. Finally, the authors' calculations indicated that a hydrological drought also occurred in Makhanda between November 2018 and January 2020.

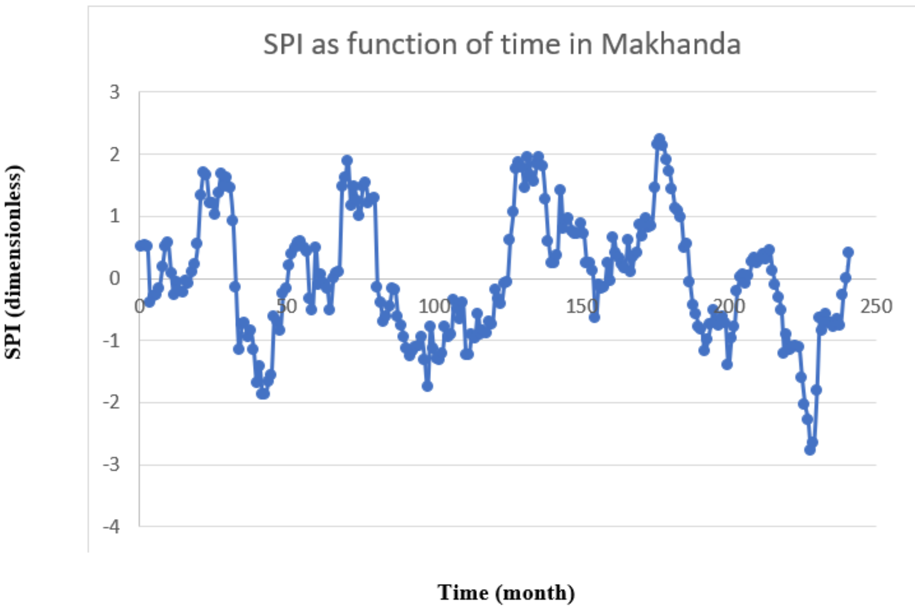

Figure 3. *The six month standard precipitation index (SPI) as a function of time from December 2000 (month 1) to December 2020 (month 241).*

Based on the SPI data, the Makana local government would face the lack of raw water for drinking water production on multiple occasions in the 2000-2020 period. Given that the *TAR* values for Makhanda were about 56 % below the global precipitation average, RWH should be seen as an additive solution for the provision of drinking water in Makana. The likelihood of the RWH deployment was investigated next by investigating the MobiSAM data.

MobiSAM was designed to strengthen the communication and information exchange between Makana residents and the local government using the e-governance platforms (Thinyane and Siebörger, 2017). That was implemented and data about the complaints or water outages are available from 2013 until 2023. During that time period, 1305 complaints or issues to address were logged by the Makana population with the local government. Out this number, 942 items were water-related, and these can be split into four categories, namely open, closed, resolved and assigned. Closed (171 items on MobiSAM) and resolved (43 items on MobiSAM) items indicate that a Makana resident had reported a water-related complaint or issue to the municipality, and their item was addressed actively by the local government. This practically means that the matter was addressed to the resident's satisfaction or that it was investigated and not found to be a problem by the local government, leading to query closure. On the other hand, open (700 items on MobiSAM) and assigned items (28 items on MobiSAM) on MobiSAM would indicate that a particular resident complaint or issue logged on the platform has not been resolved to consumer of a public good, i.e. the municipal service delivery of drinking water. Based on this reasoning, *PUWI* can be calculated by plugging in the MobiSAM numbers into Equation (4), as shown below in Equation (15).

$$PUWI = 100 \times \left(\frac{open\ items + assigned\ items\ water\ on\ MobiSAM}{The\ total\ number\ of\ water\ items\ logged\ on\ MobiSAM}\right) = 100 \times \left(\frac{700+28}{942}\right) = 77.3\ \% \qquad (15)$$

Based on the calculations in Equation (15), there is a 77.3 % that Makana residents have faced unresolved water supply issues, they had reported, between 2013 and 2023. This number is assumed to be equal to the *PUWI* values for the 2000-2020 period. Next, the probability of the Makana residents facing a water outage needs to be ascertained. Reasons for finite and non-zero values of *PUWI* and *PWSI* will be tied to the hydrological drought and water scarcity in Makhanda. It will, however, also be integrally linked to any shortcomings in the technical, human resource and other capacities in the water supply of Makana local government to its residents (secondary water scarcity). Therefore there is a correlation and mutual overlap between the components of the values of *PUWI* and *PWSI*. To untangle these is beyond the scope of this study, but the following can be deduced from this line of reasoning. The *PWSI* values were estimated as the average between 33.3 and 50.0 %, i.e. 41.7 %. The fact that 41.7 % of days are likely to be without the drinking water supply to Makana households, and 77.3 % of all water-related complaint or issues are not resolved, the probability of the Makhanda household using alternative water sources (*PAWSU*) can be approximated by the arithmetic mean of *PUWI* and *PWSI*. Therefore the *PAWSU* value for the remainder of this study will be assumed to be equal to 59.5 %. Water security for potable purposes and supply from municipal sources is thus not ensured in Makana and deployment of additional resources is needed.

Members of the author team have been working in the field of RWH in Makana for more than 10 years and they are in a position to make a reliable estimate of the number of rainwater tanks at household level in the middle-to-upper-income neighbourhood of Makhanda. This can then be used to estimate the primary Bayesian probability, as based on the definition by Kampová and Loveček (2020b), of the RWH installed capacity in the middle-to-upper-income neighbourhoods in Makhanda. This value is estimated here at 85 % and the second-order probability, i.e. reliability of this estimate is estimated at 95 %. Weaver et al. (2017) stated that the Orange-Fish River Interbasin transfer scheme supplies 78 % of all Makhanda residents, who reside in the Eastern part of Makana or in the low-income neighbourhood of the municipality. The rate of the RWH installation and use there can be estimated by rate of RWH reported by Hamer et (2018), namely 13 %. The rate of RWH installation and use at the household level in Makhanda (*RRIM*) can be calculated as shown in Equation (16).

$$RRIM = 0.22 \times 0.85 + 0.78 \times 0.13 = 0.288 \qquad (16)$$

Converting of *RRIM* into percentages, the conclusion is that around 28.8 % of households in Makhanda will harvest rainwater at the household level and that they are likely to use it as the alternative source of drinking water during municipal supply outages. The limitation of the estimates and the geographical imbalance in the rainwater tank distribution is acknowledged by the authors. *RRIM* was combined with *PUWI* and *PWSI* can provide preliminary research and DRM policy planning for the increase in the water supply resilience in Makana. This would take conditions into account the recuring hydrological drought and potential challenges in water supply and treatment for potable purposes. Water security planning must be improved and take these findings into account.

Results of this study could be ethically challenging as the last author's household was one of the study site. Therefore the ethical challenge arises from the data benefitting the last author. That benefit would be the results and possibility to optimise RWH at the last author's house, and thus optimisation of drinking water availability and usage. At the same time, the choice of study site was based on the ease of access, the lack of permit request and the need for conducting the study in a middle-to-upper-income neighbourhood and under local conditions in Makana. However, to offset some of the ethical benefits to the last author an equivalent RWH system with a 2500 litre tank was donated to a household in the low-income neighbourhood of Makana. A set of gutters, materials for the support of the rainwater tank, pump and a rainwater harvesting tank were purchased by the author team, shipped to a selected household, and installed by the household residents. Those residents were consulted and approved all materials and system chosen. The foundation/support for the rainwater was built first and allowed to set for three days. After that the rainwater harvesting rank was installed, along with the gutters, the total cost of the system and installation was 3000 ZAR (1 USD = 15 ZAR). The difference from the last author's house was that a 2500 litre tank was part of the system, and not a 1500 litre tank. This donated system remains in operation till today when the current article is being written up. The residents installed it themselves based on their choice. No power imbalance or coercion took place during the donation, installation or follow up activities. The installed RWH system in the low-income neighbourhood was not used to collect any data for the current study, except for the price of the donated system. The price was used in some calculations below but was not communicated to the members of the recipient household. The estimation of the total cost to install an RWH system in a Makana household, with a 2500 litre tank, was derived using this information and others from this paragraph. From a water security, and water supply point of view, the proposed deployment of the 2500-litres-tank RWH system would provide largest coverage and the most access to alternative water sources across Makana.

Makana had between 17000-21388 households in it based on the 2001 and 2011 census data (as per the 2014-2015 IDP; Makana, 2013-present, a, section 2.6.1.8). This further grew to 24104 by the 2023-2024 IDP drafting (as per the 2023-2024 IDP; Makana, 2013-present, a, section 2.1.1.1). Averaging these three numbers, the number of Makana households for the 2000-2020 study period can be estimated as being equal to 20831. Out of this number, 28.8 % likely have a RWH installed and so 14831 still have such a system installed. If the households' occupants do the building work and the 2020 prices of a RWH system with a 2500 litres tank are used, then the total cost of providing a RWH to each Makana household would be 44.493 million ZAR (1 USD = 15-19 ZAR). According to the South African National Department of Water and Sanitation, the Eastern Cape lost an average of 124211219 kilolitres of potable water between 2011 and 2020 (DWS, 2023). At the same time, the 2011 census showed that the Eastern Cape population was equal to 6.5 million and this increased to 7.2 in 2022 (Statistics South Africa, 2023). Taking the average of these two numbers, the Eastern Cape population is approximated by the number of 6.85 million. At the same time, the Makana population can be estimated as being equal to 79158. Using the ratio of population of Makana to the Eastern Cape, the volume of non-revenue water loss can be estimated at 1435373 kilolitres of potable water in Makana. The Makana local government charged at average 10.6 ZAR per kilolitre of potable water in 2020 (the authors' internal data). Therefore the financial loss due to non-revenue water can be estimated at 15214964 ZAR per annum in Makana. Providing each household in Makana, with a RWH system as proposed above, would be equivalent to 3 years of lost revenue on non-revenue potable water in Makana. If a grant is provided to Makana local government and the installation of RWH is accompanied by an active engagement of the municipality with the residents as their water customers, then the financial and water losses could be eliminated. Alternatively, the potable water resources could be better managed as the rainwater at household level would be delivered with minimum losses in the aging piping infrastructure. This could be done under the Integrated Urban Development Grant, as a way to connect households to water and sanitation infrastructure or to maintain, fix or improve such connections (SANT, 2020).

Estimation of the RWH installation rate and volumes of rainwater for harvesting in Makhanda

The *TVRH* values were calculated for the two scenarios of the middle-to-upper-income neighbourhood in Makhanda and the low-income neighbourhood in Makhanda using Equation (10), (12) and (14). The final calculations are shown in Equations (17)-(19)

$$TVRH = 0.0957 \times [507.7 - 1.3 \times (365.43 - 267)]m^3 = 36.3\ m^3 \qquad (17)$$

$$TVRH = 0.0957 \times 507.7\ m^3 = 48.6\ m^3 \qquad (18)$$

$$TVRH = 0.0338\ \times 507.7\ m^3 = 17.2\ m^3 \qquad (19)$$

The *TVRH* values ranged from 17.2 to 48.6 m^3 (between 17200 and 48600 litres) and the first-flush trap decrease the volume of harvested rainwater by 25.3 %. The average household size in Makana was equal to 3.85 persons between 2016 and 2020 (as per the 2023-2024 IDP; Makana, 2013-present, a, section 2.1.1.3). At the same time, the estimated minimum domestic water demand per person per day of 17.5-20.0 litres, and there are an estimated 2500 litres of RWH capacity at each household. Therefore the following estimates can be made. In the middle-to-upper-income household, the RWH system would be able to capture and store between 5.1 and 6.9 % of the estimated *TVRH* value for Makhanda. In the low-income household, the RWH system would be able to capture and store between 14.5 % of the estimated *TVRH* value for Makhanda. That harvesting would provide an alternative drinking water supply in the average-size Makana household for 32-37 days (assuming 2500 litres storage tank capacity in both types of suburbs). The maximum drinking water demand would be expected if the household occupants spent all extended period of 24 hours at home, e.g. like during the harshest phase of the COVID19 lockdown. For Makana, Madikizela et al. (2022) reported for those conditions, the average water consumption was equal to 141 ± 44 dm^3/person/day. If this level of drinking water consumption was maintained by the average Makana household, then the stored supply would last for between 4.5 days. The modelling results above indicate that the Makana/Makhanda population most likely be able to rely on the RWH systems to boost access to drinking water in conjunction with other systems and modes of delivery. From a water security point of view, the deployment of RWH would be a stop-gap measure that would need to be integrated into an integrated water management plan and policy.

Pascale et al. (2020) examined the probability of the occurrence of conditions that have led to the near day zero in Cape Town in 2018. Human actions in the Age of Anthropocene increased the probability of the three-year deficit, that had preceded the near day zero, rose 5 or 6 fold in recent years. The probability of day zero taking place again has increased between 0.7 and 80 % between the present day and the year 2100 (Pascale et al., 2020). The extent of the probability increase was a function of the anthropogenic greenhouse gas emissions (Pascale et al., 2020). Therefore the probability of rainfall deficit and also drought would be based on the intensity of human actions that catalyse climate change progression. Nantenza et al. (2022) reported the annual average of 62332 litres for the rainwater harvesting in Uganda, and so the *TVRH* estimates from this study are lower that some recent and similar study results from the African continent. The same authors reported results of a similar modelling study and they found the existing storage tanks of 8000 to 20000 litres would not be sufficient to meet the drinking water demand of 15-50 litres per person per day (Nantenza et al., 2022). Increase in the storage capacity would be needed for rainwater to meet the drinking water demand. Those modelling results are in partial contrast to the current study, where the authors propose the storage using a single size tank, in order to provide each Makana household with emergency/alternative water supply. Equality of alternative supply for water supply emergencies would take precedent over harvesting of all rainwater and its use as primary water source. Municipal drinking water supply would still need to be guaranteed by Makana local government. This is critical as the rainwater harvesting needs to be integrated into the water management and must be coupled with other protection of the environment and other components of the socio-ecological systems.

Water security of potable supply would and should be increased based on implementation of the study results. It is imperative that RWH becomes and integrated part of the water supply and management in Makana. Buy-in from stakeholders and ongoing engagement to persuade all stakeholders that RWH is not a complete and only solution to the Makan water supply problems will be critical. Security of water supply has been shown to critical to the maintenance of disaster resilience, e.g. during the recent COIVD19 pandemic. It is a risk mitigator if implemented in line with the holistic approach to the water supply and management in Makana. Water security and access to the necessary and minimum or sufficient drinking water volumes could be achieved based on the results of the current study. Water security will be an ongoing issue in Makana and South Africa more in general, as the droughts are likely to continue in the Age of Anthropocene. Actions such as the RWH installation can also increase the sense of ownership of the water systems and supply infrastructure in Makana and among its population. Resilience of water supply and the sense of ownership of the RWH systems would in turn contribute to water security in Makana.

Conclusions

Results of the current study indicate that RWH would provide a possible alternative source of drinking water in Makana/Makhanda. Storage of the harvested rainwater would be necessary and the cost of increasing the storage capacity at the household level would need to be balanced against the funding model, affordability, and the potential impact on the strained municipal finances in Makana Local Municipality. RWH should be integrated into the DRM planning and execution in Makana, as well as into the water supply management. The likely investment in RWH could offset the lost revenue due to the non-revenue municipal drinking water provision. Hydrological drought occurrence in the Makhanda area doe provide some explanation for the challenges the Makana local government faces in the provision of drinking water to the municipality’s population. The proposed strategies lead to supply of drinking water, which is more secure compared to when RWH is not installed in Makana households. Water security in terms of potable supply would thus be increased through the proposed strategies.

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