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Research paper

Identification of potential sites for rainwater harvesting structures as an adaptation to drought emergencies in Eswatini

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Water scarcity is a global problem exacerbated by the ever-increasing population and climate change, especially in arid and semi-arid regions. Different water resource management strategies, such as rainwater harvesting, have been proposed and implemented worldwide to combat water shortage. Mapping of the optimum sites where these rainwater harvesting structures can be constructed is very important. The main objective of this study was to map and identify, using GIS, optimum sites for the construction of rainwater harvesting structures (farm ponds, check dams and percolation ponds) for agricultural and peri-urban purposes in Eswatini. The optimum sites were identified by overlaying various thematic layers including land use and cover, slope, runoff potential, soil texture and depth and drainage density using ArcGIS 10.8. A general rainwater harvesting suitability map was produced for Eswatini, then potential sites for different rainwater harvesting structures were identified. The results of the study indicated that all three rainwater harvesting structures have suitable sites where they can be constructed. Check dams have potential sites which cover 22.7% of the suitable area in Eswatini, while farm pond and percolation pond sites covers 19.7% and 65%, respectively. Information on existing structures such as dams and earth dams for water storage may need to be gathered to verify the proposed sites of the rainwater harvesting structures. This study was able to identify new sites where structures can be constructed for rainwater harvesting which can improve water availability during dry seasons. Further evaluation may need to be done before implementation of these structures. Moreover, implementing this is subject to a number of other factors, such as the economy, feasibility studies as well as social implications. However, the results of this study will assist policy and decision makers in planning for potential sites for water storage as an adaptation to drought and climate change.

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INTRODUCTION

Water scarcity is a global problem intensified by the ever-increasing population and climate change, especially in arid and semi-arid regions. To improve water availability, strategic and practical water conservation and utilization measures must be prioritized. Different water resource management strategies, such as rainwater harvesting, have been proposed and implemented worldwide to combat the effect of water shortage (Ojwang et al., 2017; Tiwari et al., 2018; Wu et al., 2018; Tolossa et al., 2020; Zhang et al., 2022). Rainwater harvesting is an ancient and promising method of enhancing the water supply through inducing, collecting and storing runoff from rainfall for beneficial use (Boers and Ben-Asher, 1982; Rahman, 2017). Rainwater can be collected from impervious surfaces such as rooftops, courtyards and roads, and stored in external facilities such as tanks and ponds (Helmreich and Horn, 2009) or natural land surfaces, where the water is stored as soil moisture (Biazin et al., 2012). Rainwater harvesting has been practised in various parts of the world where water demand is higher than the available water resources (Handia et al., 2003). However, rainwater harvesting has received poor adoption in many developing countries due to potentially high implementation costs (Lindoso et al., 2018) and low institutional capacity (Sharma and Smakhtin, 2006). Contrastingly, Tiwari et al. (2018) consider rainwater harvesting as a cheaper approach to augment water supply in the current era and in the future. Therefore, exploring a range of strategies to improve exploitation and storage of rainwater to minimize the effect of severe drought is needed. The flexibility and broad application of this concept for agricultural purposes and domestic water consumption further make it a worthwhile suite of technologies to invest in by both private entities and government.

With the increase in extreme climate events (more floods and more droughts) predicted in the future in many parts of the world, especially the African continent (Ndlovu et al., 2020; IPCC, 2022), it will be useful to invest in decentralized facilities, efficient technologies and encourage policies that simultaneously promote rainwater harvesting (Mohammed et al., 2007). Several studies in different parts of the world have already demonstrated that rainwater harvesting can mitigate the impacts of drought and climate change (Lindoso et al., 2018; Tolossa et al., 2020) by improving water availability for drinking (Alim et al., 2020), agriculture and food security (McHugh et al., 2007; Kusena et al., 2017). There are different ways in which rainwater harvesting can be explored for beneficial use. Storage of the excess runoff from rainfall in external structures makes the water accessible during drier seasons. However, the sustainability of rainwater harvesting significantly depends on the variability of the rainfall, and the amount of surface runoff, as well as the available institutional support (Tiwari et al., 2018). Pandey et al. (2003) concluded that the construction of rainwater storage structures is paramount to collect runoff during flood events and could possibly increase the accessible surface runoff.

Mapping of the optimum sites where these rainwater harvesting structures can be constructed is very important (Wu et al., 2018). The selection of optimum rainwater harvesting sites depends on a number of factors. Depending on the objective of the study or available data, more factors can be incorporated when identifying suitable sites for rainwater harvesting. Many studies have used biophysical factors such as slope, rainfall of the area, land use/cover and soil type as a base study towards rainwater harvesting potential. However, socio-economic factors have been integrated with biophysical factors in recent studies, to improve the selection of potential rainwater harvesting sites (Ammar et al., 2016). The use of only biophysical factors for the selection of potential rainwater harvesting sites is equally important and necessary, especially in data-scarce countries.

Recently, different methods and tools for mapping and identifying optimum sites for rainwater harvesting, such as the use of geographic information systems (GIS), have been advancing, due to the promising potential of the technology (Tiwari et al., 2018; Wu et al., 2018; Haile and Suryabhagavan, 2019; Mugo and Odera, 2019; Hashim and Sayl, 2021). GIS has been identified as an initial and key stage to identifying rainwater harvesting suitability, and integration with other methods such as multi-criteria analysis (MCA) is recommended for a better outcome (Preeti et al., 2022). The methodologies require the availability of accurate data, particularly in countries where rainwater harvesting is necessary for improving water security and water resource development (Haile and Suryabhagavan, 2019). For example, in Southern Africa, climate projections for the future indicate an increase in extreme events, with droughts being a major feature (Nkhata, 2021). The impacts of past drought events have already shown notable effects on the society, environment and economy in this region. This is because more than 60% of the population depends on rainfed agriculture for their livelihoods (Masih et al., 2014; Sheffield et al., 2014; Sifundza et al., 2019). Efficient and sustainable use of rainwater harvesting techniques has a significant potential of improving water availability for rainfed agriculture in arid and semiarid areas (Mbilinyi et al., 2005).

Various researchers have used methodologies to find rainwater harvesting sites in specific cities, river basins or at the catchment scale within a country. In this study, a different approach has been employed, whereby the mapping of potential rainwater harvesting sites has been done on a national scale. A better understanding of the rainwater harvesting potential within the national boundaries allows for improvement in the national water management framework by integrating rainwater harvesting within water resource development plans. The main objective of this paper was to assess the potential of rainwater harvesting and identify optimum sites for the construction of rainwater harvesting structures (farm ponds, check dams and percolation ponds) for agricultural and peri-urban purposes in Eswatini. Criteria for identifying optimum sites for rainwater structures were adopted from the Integrated Mission for Sustainable Development 1995 (IMSD, 1995) and Food and Agriculture Organization (FAO, 1977) guidelines of 1977 (Table 1). Optimum sites in this study are defined by the potential of the area to retain and store runoff on depressed land (Preeti et al., 2022; Sayl et al., 2020). This was based on the use of multi criteria analysis integrated in a GIS tool. Suitability of rainwater harvesting in natural depressions was chosen because these are cost effective and easily implemented, especially in developing countries like Eswatini.

METHODOLOGY

Study area

This study was conducted in Eswatini, a land-locked country situated in Southern Africa, between Mozambique and South Africa, and located at 26° 30' S; 31° 30'E. Even though the country is one of the smallest in Africa, it has a diverse climate and topography. It has a subtropical climate with summer rains, with approximately 75% of the precipitation falling between October and March (FAO, 2005). Eswatini is divided into four main climatic regions (also known as agroecological zones): the Highveld, Middleveld, Lowveld and Lubombo plateau. However, recently, researchers have further divided the Middleveld into the wet Middleveld and drier Middleveld, and the Lowveld to eastern and western Lowveld due to the variation within these regions, as shown in Fig. 1. These regions range from cool and mountainous areas (Highveld) to hot and dry areas (Lowveld). The Highveld has the highest annual rainfall (Table 2). The Lowveld receives the least rainfall, ranging between 400 and 550 mm/a. The Highveld has sub-humid and temperate climatic conditions, whereas the Lowveld is semi-arid and warm and may record temperatures up to 40°C in summer. The mean annual temperature varies from 16°C in the Highveld to 22°C in the Lowveld.

The main land-use activities in Eswatini include subsistence farming, commercial farming (mostly sugarcane and citrus), commercial cattle ranching (both private and government) and conservation (for example, protected areas and ecotourism reserves). Maize is the main crop grown by subsistence farmers; however, there is an increasing number of subsistence farmers who are venturing into sugarcane production, especially those with irrigation facilities.

Table 1. IMSD guidelines for rainwater harvesting structures suitability (FAO, 1977; IMSD, 1995)

Rainwater harvesting structure	Rainfall (mm)	Slope (%)	Runoff potential	Porosity and permeability	Stream order	Catchment area ($\times 10^4$ m^2)
Farm ponds	>200	0–5	Medium/high	Low	1	1–2
Check dams	<1 000	<15	Medium/high	Low	1–4	>25
Percolation ponds	<1 000	<10	Low	High	1–4	25–40

Table 2. Average annual rainfall and mean temperatures in the main agro-ecological zones of Eswatini (Matondo and Singwane, 2017; Mlenga and Jordaan, 2020)

Ecological zone	Rainfall (mm)	Mean temperature (°C) (min–max)
Highveld	700–1 550	16.3–17.6
Middleveld	550–850	19.3–20.5
Lowveld	400–550	21.3–22.3
Lubombo plateau	550–850	19.2

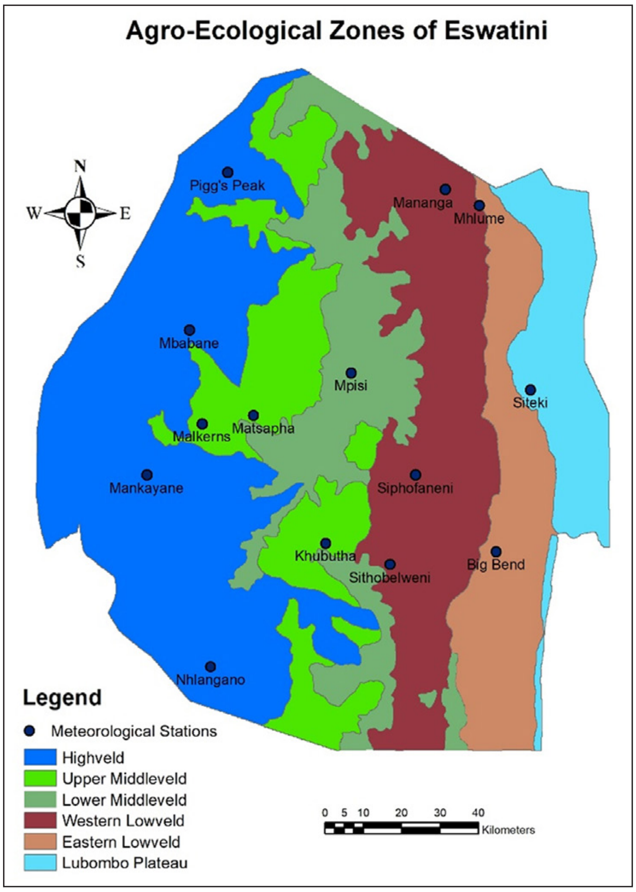

Figure 1. Agro-ecological regions of Eswatini

Dataset collection and preparation

In this study, the following freely available data were obtained and processed:

- Rainfall: monthly rainfall data for Eswatini from 1981 to 2020 for 14 meteorological stations was obtained from Eswatini Meteorological Service. It was further used in the analysis and preparation of a mean annual rainfall map for Eswatini.
- The digital elevation model (DEM) was derived from the topographic map of Eswatini.
- Slope and stream network maps: The DEM was used to prepare the slope and stream order maps using ArcGIS version 10.8 software.
- Soil and land-use/cover maps: The soil-texture map and land-use maps were obtained from the University of Eswatini, Department of Agricultural and Biosystems Engineering. The soil-texture map was used to prepare the hydrological soil group map.

Runoff potential

The Soil Conservation Service Curve Number (SCS-CN) method was used to determine the potential runoff depth in the study area. This method was found by Fan et al. (2013) to be effective in areas with minimal data and ungauged watersheds. The calculation was based on the runoff curve Number (CN), which is actually the estimate of the impact of land use/cover and soil on rainfall-runoff processes (Zhan and Huang, 2004). The antecedent moisture conditions were also important as input to develop the curve numbers. A curve number map was first produced using ArcGIS 10.8 and based on the antecedent soil moisture conditions (AMCI), hydrological soil groups and land use and cover. The hydrological soils groups were classified using the soil texture and depth, as explained by Neilsen and Hjelmfelt (1998). The soil depth and texture determine the rate of infiltration and consequently the surface runoff (Abraham et al., 2019). Runoff depth was then estimated using the curve numbers and mean annual rainfall. Rainfall volume data were used instead of rainfall intensity because of a lack of rainfall intensity data in Eswatini. To estimate the direct runoff from storms, the rainfall-runoff equation given by Satheeshkumar et al. (2017) was used.

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \quad P > 0.2S \tag{1}$$

where: S is watershed storage, mm; Q is potential runoff depth, mm; P is rainfall, mm.

S is a function of the CN value as shown in Eq. 2.

$$S = \frac{25\,400}{\text{CN}} - 254 \tag{2}$$

Rainwater harvesting suitability

ArcGIS 10.8 was used to overlay thematic maps to identify the potential sites for rainwater harvesting in Eswatini. Figure 2 shows which thematic layers were used and how these layers were overlayed to determine the suitable rainwater harvesting sites. The following layers were used to determine rainwater harvesting suitability: land use and land cover, slope, rainfall, runoff potential, soil depth and soil texture. Vector themes were converted to grid themes because the model builder works in a raster environment with grid layers. Different suitability values were assigned for the different layers (as classified by De Winnaar et al., 2007; Kahinda et al., 2008; Dile et al., 2016). Each thematic layer was reclassified from 1 to 5 with the most suitable area classified as 5 and the least suitable classified as 1 (Table 3). A weighted overlay analysis was performed to determine which

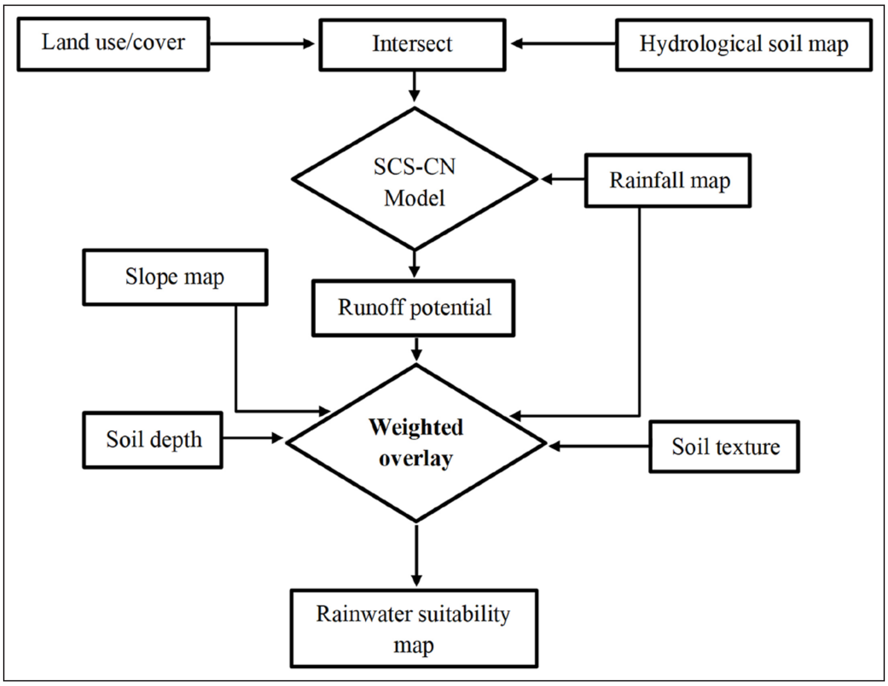

Figure 2. Flowchart for rainwater harvesting suitability map generation (adapted from Sacolo and Mkhandi (2020)

Table 3. Rainwater harvesting suitability ranking

Rainfall (mm)	Slope (%)	Runoff potential	Soil depth	Soil texture	Land use/cover	Suitability
0–100, >1 000	>30	64–70	<0.2	Loamy sands/sands	Settlement area	1
100–200	15–30	71–78	0.2–0.3	Clays	Forestland	2
200–400 800–1 000	<2	79–84	0.3–0.4	Sand loams	Rangeland Water bodies	3
400–600	8–15	85–90	0.4–0.75	Sandy clay loam		4
600–800	2–8	91–95	>0.75	Sandy clays	Agricultural land	5

areas are most suitable for rainwater harvesting by applying different percentages of influence to the factors. The advantage of the weighted overlay analysis is that it does not involve any risks; instead, it analyses tradeoffs between the factors. Furthermore, De Winnaar et al. (2007) recommends this method because with further analysis it can also inform planners what water storage facility can be filled in a season in a particular potential rainwater harvesting site. Additionally, the use of GIS for determining the potential rainwater harvesting sites improves the level of accuracy for exactly locating the areas, due to the capability of GIS to use spatial information in a unifying manner and to produce maps (Preeti et al., 2022).

Potential sites for RWH structures

In addition to the general rainwater harvesting suitability map, further analysis was performed to identify sites where water storage structures for rainwater harvesting can be constructed. Structures selected for this study were farm ponds, check dams and percolation ponds. The potential sites for these rainwater harvesting structures were identified using the Integrated Mission for Sustainable Development (IMSD) criteria of 1995 and Food and Agriculture Organization (FAO) guidelines of 1977 as shown in Table 1.

Farm ponds

Farm ponds are popular rainwater harvesting structures that are widely used for storage of surface runoff. They require a relatively flat area with a slope of less than 5% and medium to high runoff potential, as shown in Table 1, in order to retain as much as possible of the surface runoff. A very important criterion that needs to be considered when identifying sites suitable for farm ponds is that the land use should also be suitable for agriculture, as the water stored in the farm ponds is mainly for providing supplementary irrigation during water scarcity (Buraihi and Shariff, 2015; Ammar et al., 2016). Moreover, farm ponds can be constructed in areas which receive rainfall greater than 200 mm, and require a catchment area of between 1 and 2 ha.

Check dams

Check dams are also popular structures in many countries because they not only serve as rainwater storage facilities but also help in addressing soil erosion problems. Water stored in check dams is mostly restricted to stream courses, and a height of around 2 m, depending on the stream width (Ammar et al., 2016). They are most effective in areas which receives annual rainfall of less than 1 000 mm. Additionally, check dams require a catchment area that is greater than 25 ha, with slopes of up to 15%. These structures are usually constructed on less permeable soils such as loamy clay to allow for minimum infiltration and greater retention of surface runoff (Saha et al., 2018). Water captured in check dams can be used for number of activities, such as crop production and domestic water supply if properly treated.

Percolation ponds

Percolation ponds are artificially made structures that are used to capture surface runoff from rainfall and store water for groundwater recharge. They are generally built in areas that lie are across streams and larger dongas so that they capture surface runoff (Ammar et al., 2016). These rainwater harvesting structures require adequate catchment areas of not less than 25 ha, can have a slope of up to 10%, and need soils are highly porous and permeable for water to easily percolate down to groundwater resources. Percolation ponds are important as rainwater harvesting structures because they assist in replenishing groundwater resources. Groundwater resources are an alternative source of water in areas where surface water resources are inadequate; therefore, preventing their depletion is important.

RESULTS AND DISCUSSION

Rainfall

The mean annual rainfall was based on the long-term annual rainfall data (1981–2020) of Eswatini from 14 meteorological stations. These stations represented the different agro-ecological zones of the study area, i.e., the Highveld, the Middleveld, the Lowveld and the Lubombo plateau. The rainfall for the 14 stations was then interpolated for the whole study area using inverse distance weighted (IDW) interpolation. Basically, the north-western part of the study area receives higher rainfall than the eastern part of the country. Figure 3a shows the annual rainfall distribution in Eswatini. The maximum mean annual rainfall was found to be 1 416 mm in Mbabane, which is on the Highveld of the study area, while the minimum was 550 mm, observed at Big Bend in the Lowveld of the country.

Land use and land cover (LULC)

The land use and land cover of any watershed influences evapotranspiration and the generated surface runoff. The LULC map of Eswatini is given in Fig. 3b and coverage in the study area is summarized in Table 4. Land use and land cover in the study area were classified into 10 major classes: bare land, bushland, large cropland plantation, small-scale cropland, forestland, grassland, riverine vegetation, urban areas, water bodies and woodland. The most dominant land use is agricultural production (both small-scale and large-scale plantations and cropland), which covers about 25.9% of the land surface of Eswatini. This is followed by woodlands which cover about 23.9% and are mostly in the eastern part of Eswatini. Land used or covered by water bodies, agricultural production and dense forest has a good potential for rainwater harvesting (Ammar et al., 2016).

Table 4. Land use and land cover (LULC) in Eswatini

LULC	Area (ha)	Percentage (%)
Bare area	2 073.68	0.12
Bushland	373 084.71	21.58
Cropland plantation	94 398.25	5.46
Cropland small-scale	353 531.20	20.45
Forestland	134 248.49	7.77
Grassland	319 686.09	18.49
Riverine vegetation	9 724.01	0.56
Urban area	11 075.06	0.64
Water bodies	18 053.03	1.04
Woodland	412 688.02	23.87
Total	1 728 563	100

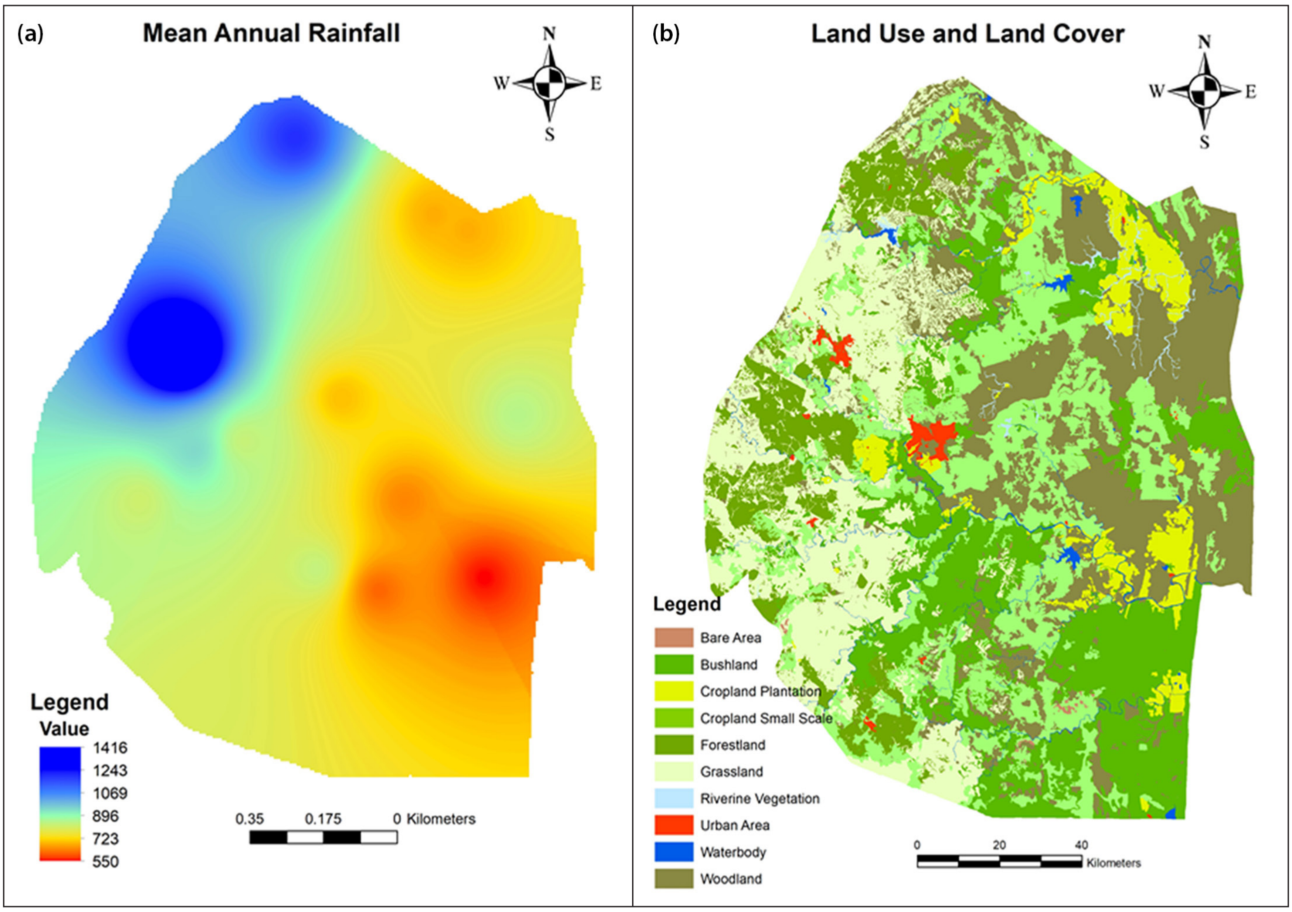

Figure 3. Thematic maps of (a) average annual rainfall, and (b) land use and land cover of Eswatini

Slope

Slope affects the speed of the surface runoff and thus influences how much water can be infiltrated into the soil or captured for storage. It is thus a very important factor to be considered when identifying sites suitable for rainwater harvesting (Agarwal et al., 2013). Figure 4a shows that the slope in Eswatini reaches up to 17.5% and was classified for this study as nearly level (0–5%), moderate slope (5–10%), strong slope (10–15%) and moderate steep slope (>15%). The results indicate that 87% of the land surface of Eswatini is 'nearly level' with only 0.02% land which is moderately steep.

Stream network

The stream network of the study area was classified into 4 classes using the Strahler stream ordering method (Strahler, 1957). Only three (3) streams were found to be of the 4th order, and the rest of the streams were Order 3 and below, as indicated in Fig. 4b. Different rainwater harvesting structures differ in their stream order requirements, as indicated in Table 4. For example, farm ponds are suitable on 1st-order streams, while check dams may be constructed on up to 4th-order streams.

Soil texture and hydrological soil groups (HSG)

The soil map of an area is important in determining rainwater harvesting potential as the soil texture gives an indication of the permeability of that particular soil. For optimum rainwater harvesting, fine- and medium-textured soils are desirable as they retain water more than coarse-textured soils. However, if the purpose of the rainwater harvesting is to recharge groundwater, more permeable soils are desired. The soil texture map shown in Fig. 5a revealed that Eswatini is mostly covered by loamy to clayey soils. The soils were further analysed into HSG, based on their runoff and infiltration potential. The HSG classification was based on the United States Department of Agriculture (USDA) Natural Resource Conservation Service (NRCS) (2009) classification, which uses the infiltration rate and drainage conditions, amongst other soil features (Hashim and Sayl, 2021). The soils were classified into 4 hydrologic soil groups according to their runoff potential; A (low), B (moderate), C (high) and D (very high), as described in Table 5. According to Fig. 5, Soil Group A, which is mostly sandy soils and gravel, covers 21% of the study area. Group B soils are moderately drained with loam to silt loam textures and cover 37% of the study area, mainly in the central-western part of Eswatini. Group C soils cover 18% of the study area and these soils are well drained. Group D has the second highest coverage, at 24%, and occurs mainly in the eastern part of Eswatini. This group has high runoff potential and is optimal for constructing rainwater harvesting structures (Mahmood et al., 2020).

Runoff potential

Rainfall-runoff modelling is a non-linear and compound process, which is affected by many physical and often interconnected factors. Runoff potential depth estimation requires detailed and accurate spatial information on the study area, and countries like Eswatini are data-scarce, which makes modelling of such parameters very difficult. The thematic layers of soil, rainfall and LULC were integrated in GIS, with the runoff potential estimates corresponding to different hydrologic soil groups. LULC and antecedent moisture conditions were derived by applying the SCS-CN method. The curve numbers (CN) ranged from 34 to 72 across the entire study area (Fig. 6a). The lower CN values were observed where there are sandy soils with poor vegetation cover, such as bushland areas. Higher CN values were observed in the eastern part of the country where the soils are mainly loam to clay, and this is where most of the commercial agricultural production occurs.

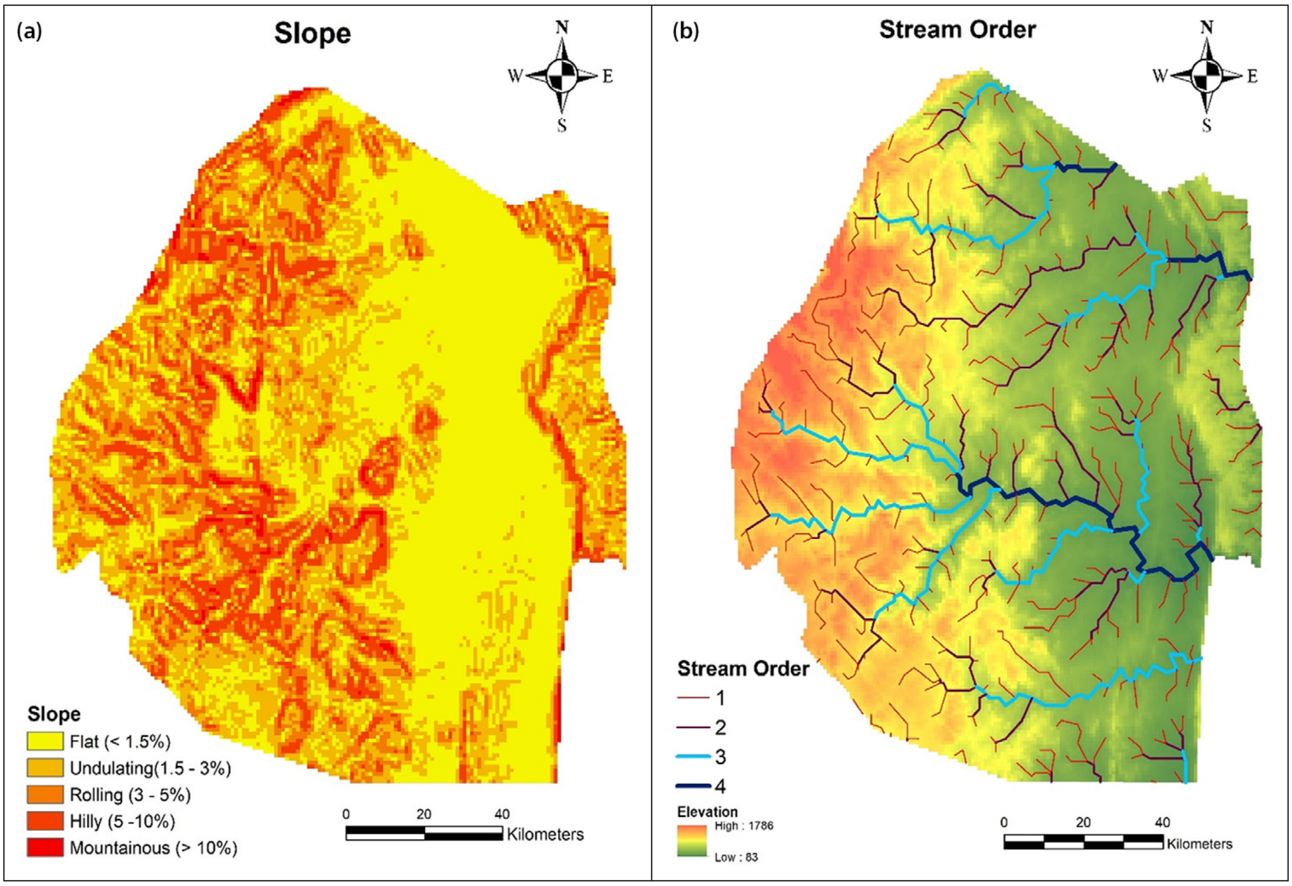

Figure 4. Thematic maps of a) slope and (b) stream network of Eswatini

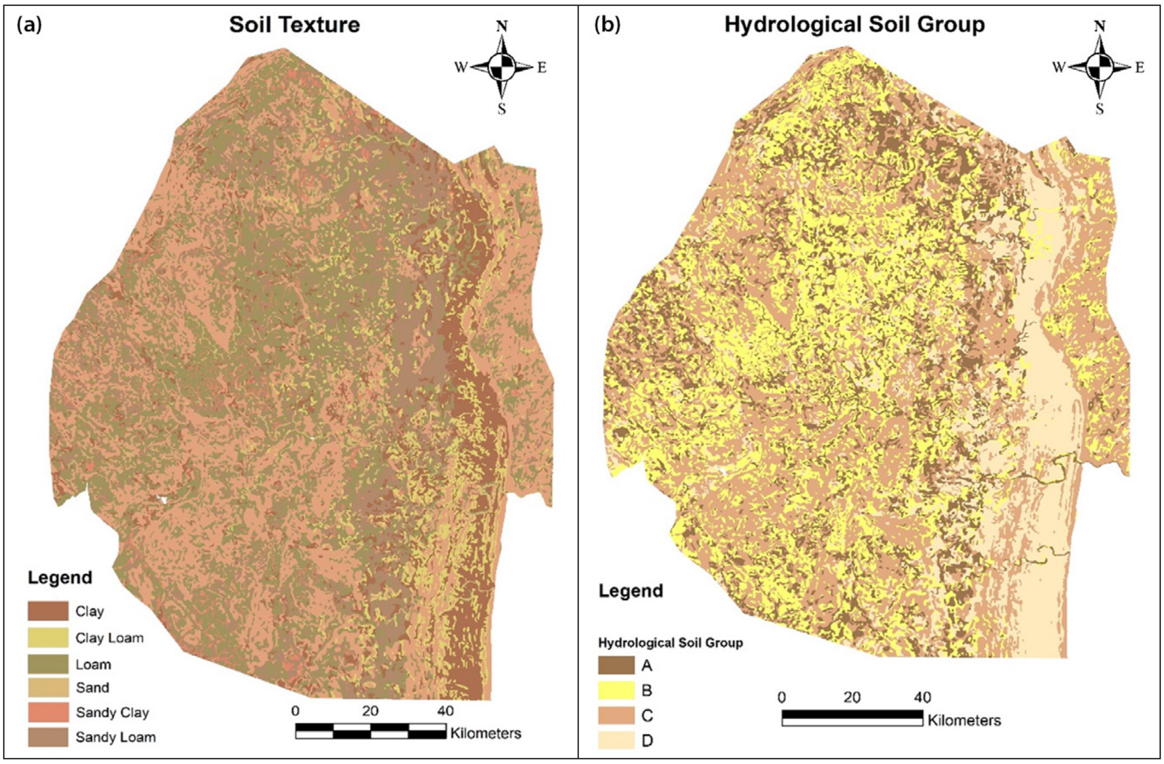

Figure 5. Thematic layers of (a) soil texture and (b) hydrological soil groups of Eswatini

Table 5. Hydrological Soil Group classification (USDA, 2009)

Group	Types of soil	Characteristics
A	Sand, loamy sand, sandy loam	Low runoff, high infiltration
B	Silt loam, loam	Moderate infiltration rates
C	Sandy clay loam	Low infiltration rates
D	Clay, silty clay loam, sandy clay, silty clay	High runoff, very low infiltration

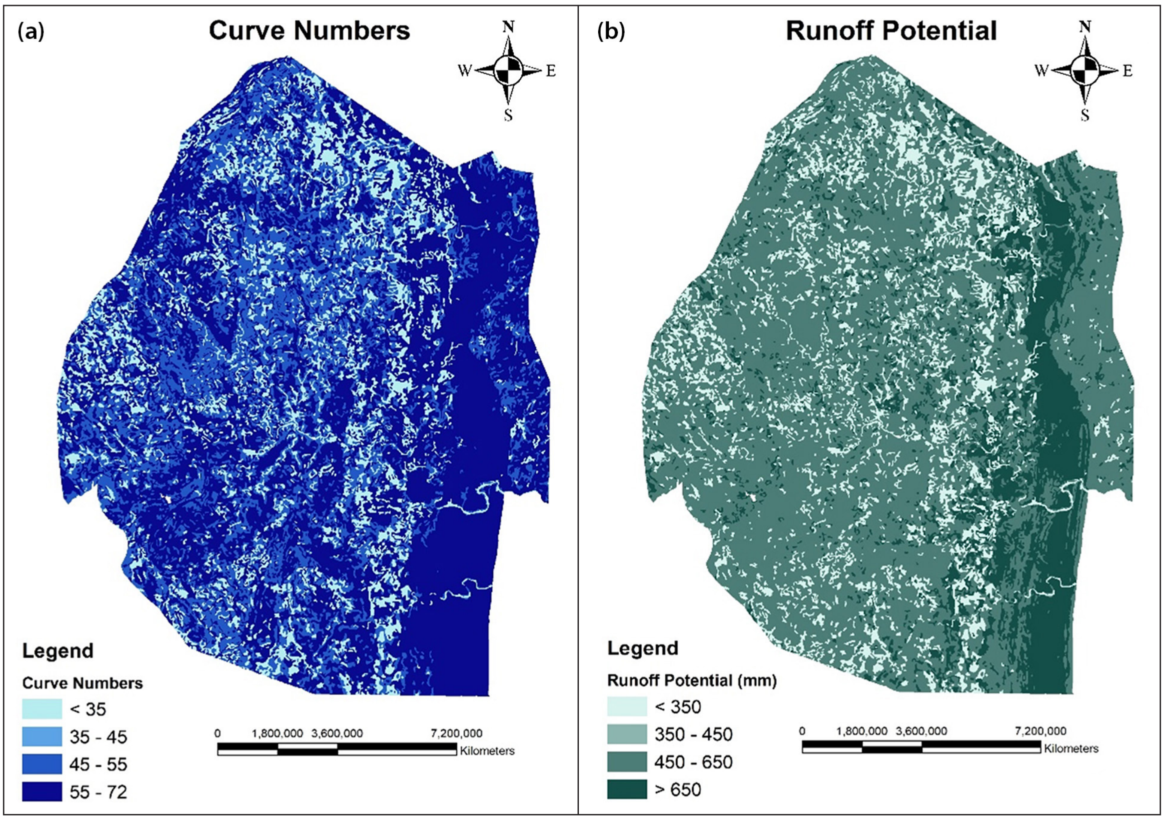

Figure 6. (a) Curve number distribution; (b) runoff depth potential

The mean annual runoff potential depth was then estimated based on the mean annual rainfall (40-year mean, 1981–2020) data for Eswatini. The potential annual runoff depth for the study area ranged from 290 mm to 796 mm (Fig. 6b). The distribution, volume and intensity of rainfall are very important parameters in determining the potential runoff depth (Mugo and Odera, 2019). However, the lack of rainfall intensity data may result in less accurate but still usable information, especially for planning purposes in water resources management. Generally, higher rainfall areas should produce higher runoff even though the actual runoff could depend on the slope, soils, land cover and other factors. Contrastingly, the south-eastern part of Eswatini has a higher runoff depth potential, yet it does not receive much rainfall compared to the northern part of the country. This could be caused by the soil textures (Hashim and Sayl, 2021), which are mainly clayey and are in Hydrological Soil Group D, which has a low infiltration rate and high runoff potential, while the northern and western parts of the country have mostly sandy loam soils. The area is also covered by cropland or plantations, which makes it well managed and well suitable for farm pond construction.

Rainwater harvesting suitability

The rainwater harvesting suitability map was generated by using weightings assigned to the thematic layers ofslope, rainfall, land use and cover, runoff potential and hydrological soil groups. Different weights were assigned to the thematic layer inputs, as suggested by Singhai et al. (2019). The weights or influence of each layer were assigned as follows; slope (50%), hydrological soil group (20%), LULC (15%), rainfall (10%) and runoff potential (5%). The suitability of rainwater harvesting was classified into 4 categories: less suitable, moderately suitable, highly suitable and very highly suitable. Classification of the suitability categories and also the input layers used can depend on the objective of the study and the decision that needs to be taken in that particular water resource management context (Tumbo et al., 2013; Rahman, 2017). These categories were chosen in this study because it can give water resource planners enough technical aspects of rainwater harvesting to consider for a start. However, when more objectives are to be considered, such as social and economic, more thematic layers may be needed to develop the suitability map (Rahman, 2017).

Figure 7a indicates that less suitable represents 13.2%, moderately suitable represents 44.3%, and highly suitable represents 35.8%, while very highly suitable represents 6.7% of the entire study area. The moderately suitable area is mostly covered by bushlands and grasslands on loam to clay soils. The area is mainly in the Lowveld of Eswatini which has flat land (i.e. slopes of less than 1.5%) and is where extensive agricultural production is practised due to the favourable climate. Similar results were observed by Haile and Suryabhagavan (2019) in a study to identify potential rainwater harvesting sites in Ethiopia, where the suitable area for rainwater harvesting was covered by bushlands and grasslands. Moreover, these results conform with the study by Hashim and Sayl (2021) which demonstrated that areas with fine slopes, clay loam soil textures and intensive cultivation were suitable for rainwater harvesting. Highly and very highly suitable areas were found to mostly be on the Highveld, Middleveld and the Lubombo Plateau. This is because these regions receive more rainfall than the Lowveld.

The results indicates that check dams have potential sites which cover 22.7% of the suitable area in Eswatini, while potential farm ponds and percolation ponds cover 19.7% (Fig. 7b) and 65%, respectively. Information on existing structures such as dams and earth dams for water storage needs to be gathered to verify the proposed sites of the rainwater harvesting structures. Proposed sites may not overlap with existing structures, and this will assist

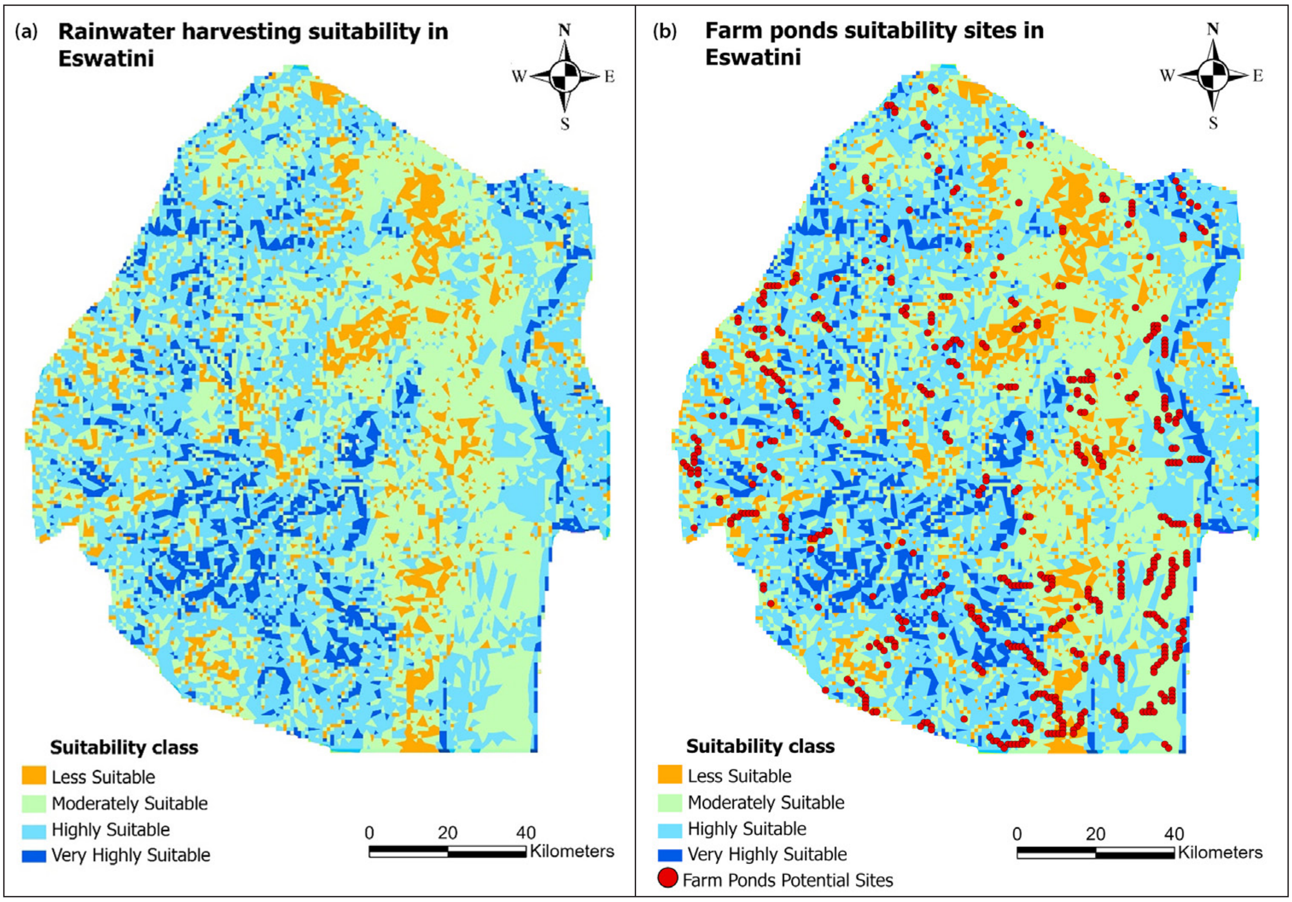

Figure 7. (a) Final rainwater harvesting suitability map; (b) potential sites suitable for farm ponds in Eswatini

in identifying new sites where structures can be constructed for rainwater harvesting and which can improve water availability during dry seasons. Further evaluation may need to be done before implementation of these structures. Moreover, economic, political and social implications are important to consider before such structures may be implemented.

The identification of potential areas suitable for rainwater harvesting is a key step in enhancing drought adaptation and water resource management (Preeti et al., 2022). This study demonstrated that integrating hydrological and topographical data could provide the basis for identifying areas suitable for rainwater harvesting in climatic and environmental conditions similar to Eswatini. The intensity and distribution of rainfall is a major factor to consider when identifying sites as suitable for rainwater harvesting (Tsubo et al., 2005). It is important to analyse the patterns from long-term rainfall to determine the high surface runoff yielding sites from heavy, short-duration storms, and to harness the runoff for future use (Yang et al., 2024). In addition, the study demonstrated that the use of digital elevation models (DEM) plays a crucial role in identifying rainwater harvesting sites, as through them the variations in the topography of an area are determined (Adham et al., 2018; Ammar et al., 2016). The topography of an area influences the speed and volume of surface runoff generated, as well as what type of rainwater harvesting structure can be constructed. For example, farm ponds require a flatter slope (>5%) while check dams can be constructed on sites with steeper slopes (up to 15%). The practical applications of the findings from this study include improving water security, supporting agriculture and contributing to groundwater recharge. These demonstrate the many benefits of rainwater harvesting. By including this information in national water management strategies, Eswatini can build greater resilience towards climate change. To encourage farmers to adopt rainwater harvesting, for example, governments can include supportive policies such as providing incentives and subsidies to those practicing rainwater harvesting (Zingiro et al., 2014). This study emphasizes the importance of innovative and sustainable approaches to managing water resources in the midst of global environmental challenges.

CONCLUSION

Rainwater harvesting is a potential technique that is widely used to improve water availability in water-scarce regions. This study demonstrated a GIS methodology to map and identify suitable sites for the construction of rainwater harvesting sites to improve water utilization and conservation in Eswatini. Based on the results of this study, Eswatini is generally suitable for rainwater harvesting (44.3% moderately suitable, 35.8% highly suitable areas and 6.7% very suitable). Areas with loam to clay soil textures and covered by bushlands in the central to eastern part of Eswatini are moderately to very suitable for rainwater harvesting. Moreover, percolation ponds have a larger suitable area (65%) than farm ponds (19.7) and check dams (22.7%). These results show the potential of capturing and storing water during periods of excess rainfall, enhancing water availability during drought periods. This study provides a baseline for drought adaptation in Eswatini and areas of similar context where droughts are an urgent concern. To promote rainwater harvesting and water conservation, there is a need to emphasize rainwater harvesting in national water management frameworks as a viable water management strategy. However, implementing this practically is subject to a number of other factors, such as the economy, feasibility studies as well as social implications. Future work should consider combining the technical analysis with the involvement of other stakeholders such as communities, farmers, government, etc., for a more comprehensive approach. Moreover, the availability of accurate data is required for the method to be more effective, particularly in areas where rainwater harvesting is needed for improvement of water security, such as in Eswatini.

AUTHOR CONTRIBUTIONS

Lungile Senteni Sifundza was responsible for conceptualizing the study, methodology, analysis of results and writing of the initial draft and review of the manuscript. Heinz Beckedahl was also involved in conceptualizing the study, results interpretation as well as writing and review of the manuscript.

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