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APPLICATION OF GIS AND ANALYTICAL HIERARCHY PROCESS FOR DETERMINING POTENTIAL SITES FOR RAINWATER HARVESTING TECHNIQUES IN SOUTH DARFUR

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Abstract

The purpose of this study is to create maps that identify potential sites for rainwater harvesting techniques (RWHT) in South Darfur State (SDS), using the Nyala basin as a case study. The basin experiences flash floods, which generate significant amounts of runoff. The RWHTs aim to conserve and maximize the available water resources in order to improve crop productivity. After conducting a literature review and consulting with experts in the field, seven RWHTs were selected for the study: runoff basin system, contour furrows, and flat, flood, pond, check dam, on-farm pond, and bench terraces. The data analysis was carried out in the ArcGIS environment and involved spatial analysis and data re-classification, supported by multi-criteria analysis. The multi-criteria analysis consisted of five selection criteria (rainfall, runoff, land use, slope, and soil texture), each with sub-indicators to assign relative weight for each RWHT. These selection criteria were based on an extensive literature review and five expert-based surveys that assessed the impacts of RWHT on the study area using an Analytic Hierarchy Process (AHP). The consistency ratio between the experts' opinions was evaluated using the pair-wise comparison. Final weights were computed for each criterion, and the method of spatial analysis and data re-classification was employed to generate the required suitability maps. The results show that runoff basin systems are recommended for use in the southwest high-rain parts of SDS, and it is the most suitable technique for about 30% of the area of SDS. Contour furrows, flat and terrace techniques are highly suitable for 70% of the state area with moderate rainfall to grow pasture. Flooding techniques are not recommended except in the high rainfall southern areas near Bahr El Arab. The check dam and pond techniques are suitable in the middle to the southern areas that are occupied by small surface streams running towards Bahr El Arab. Farm ponds or flooding techniques are not suitable for Debla's hilly areas or the northern areas with low rainfall. For the Jabal Mara area, it is recommended to employ bench terraces. Overall, this approach can help decision-makers efficiently plan water resource management in arid dry areas suffering from water shortages, ensuring sustainable development of water resources.

Keywords: *Rainwater Harvesting Technique; ARC-GIS; Analytical Hierarchy Process; Suitability Maps; South Darfur State.*

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INTRODUCTION

This study aims to assess water resources in areas with uneven water distribution and severe spatial and temporal water shortage, particularly in urban centers with large concentrations of internally displaced people and areas of contact between pastoralists and farmers. The South Darfur region of Sudan, covering an area of 78,000 Km2 with a population of 3,582,667, is a typical case where the Darfur conflict was initiated by competition over stressed natural resources, particularly water scarcity. The Darfur Joint Assessment Mission has highlighted the importance of water as a determinant factor for sustainable recovery, development and peace in the region (Sulik 2011). Therefore, any plans for re-settlement require a detailed assessment of water resources, including water demand for various uses and provision of water supply from reliable sources, taking into account sustainability and rational management strategies.

Irregular rainfall patterns and a lack of precipitation storage facilities have caused water shortages in southern Darfur, severely affecting people's access to water and often leading to livelihood insecurity (Young and Osman 2006). Increasing population growth and expansion of agriculture activities further increase the stress on harvested and uncertain water supplies. Additionally, the current political situation poses another accessibility limitation to water resources for southern Darfur. The water shortage issues include both the domestic and agricultural sector. Therefore, there is a need to explore non-conventional water resources, such as rainwater harvesting techniques (RWHT), to alleviate water shortages in the Southern Darfur of Sudan. The implementation of RWHT is promoted on a small scale by local societies and non-governmental organizations to improve temporal and spatial water shortage for domestic and agricultural uses. The success of RWH systems depends heavily on their technical design and the identification of suitable sites and techniques (Ammar, Riksen et al. 2016).

The identification of appropriate sites for the various RWHTs in large areas was a great challenge (Srivastava 1996). Several methodologies have been established for the identification of RWH site suitability maps in different areas (Mahmoud and Alazba 2015). Some methodologies integrate multi-criteria decision-making (MCDM) based on the formation of models (Neitsch 2005), while others used the TOPSIS multi-criteria decision analysis (Hajkowicz and Higgins 2008). Most studies rely on the analysis of site characteristics to determine suitability rather than on the analysis of technical characteristics. Therefore, the preparation of RWHT suitability maps is crucial for planning purposes.

To perform a successful assessment, planning, design, operation and management of water resources systems, an adequate water monitoring and information system is a prerequisite. It requires a meaningful database by utilizing a geographical information system as a tool to aid in the spatial location of the integrated element of water resources systems. These elements include water harvesting techniques, and conjunctive use of surface water of the Wadi system and groundwater using artificial recharge is critically needed in South Darfur in particular (Abdo and Salih 2011). Traditional water harvesting systems have been used in South Darfur for a long time, but many water harvesting projects have collapsed due to technical faults, the selection of the wrong technique for the wrong place, and poor design (Abdo and Salih 2011).

Considering Wadi Nyala, though the estimated average flow of the Wadi is about 40 MCM/year, a maximum of only 6 MCM/year is currently utilized mainly through groundwater abstraction from the alluvial aquifer. According to McDougall (McDougall 2021), aquifer recharge and modification of the pumping pattern from water harvested from Wadi Nyala the abstraction from the aquifer could be doubled. South Darfur has enough water resources that can secure the present and future demands if properly managed. However, the old approach of fragmented development needs to be changed to a more coordinated or integrated approach in which all the available resources are utilized conjunctively in a manner that maximizes the benefits from utilization. In South Darfur, surface and

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groundwater are often available at the same location but surface water availability is highly seasonal and highly variable, typical to the characteristics of arid and semi-arid areas. As the pattern of surface water availability in South Darfur is considerably different from the pattern of water demand, it could be very useful to exploit groundwater at times of low or no surface water availability and recharge the harvested surface water into groundwater at times of high surface water availability using artificial recharge methodologies. Water Harvesting Techniques could play a vital role in securing water availability in South Darfur.

MATERIALS AND METHODS

Study Area: The South Darfur (SDS), Sudan, is located in the Southwest of Sudan (Figure 1) with an area of about 5860 km. It has a population of 2.9 million people distributed in 11 administrative governorates (Sudan 2007)

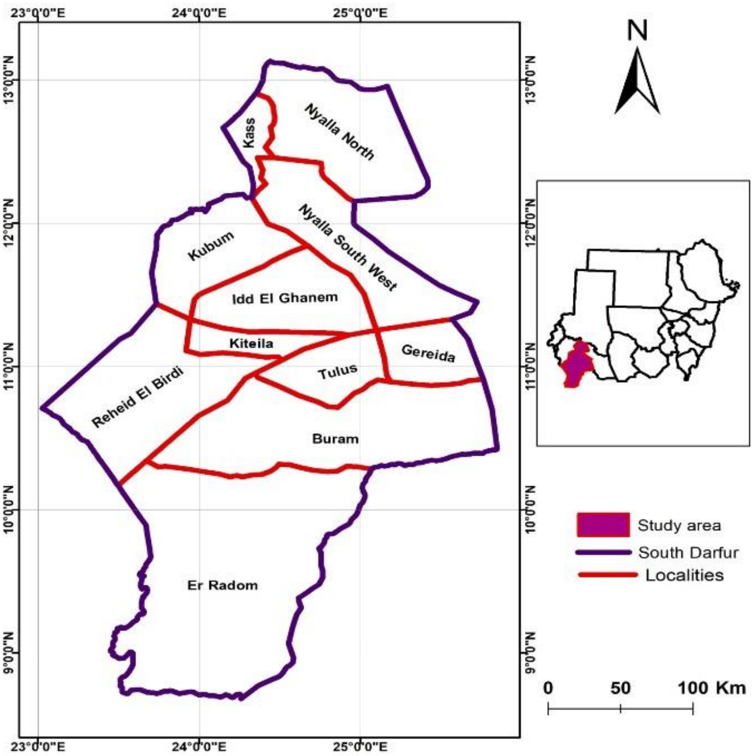

Figure 1: Location of South Darfur (SDS), Sudan Study Area

The climate in the state is characterized by hot summers and mild winters. The amount of rainfall varies between 300 mm in the north to 800 mm in the south. Rainfall in South Darfur is highly seasonal and variable in space and time, typical of arid zones. The natural cover consists mostly of savannah wood forests. Surface water is characterized by many seasonal Wadis, mostly originating from Jebel Marra or its adjacent high-country sides. There are three famous Wadis systems joined by different tributaries that trend to the south or southwest to join Bahr El Arab, a tributary of the Nile. Many towns and big villages are situated on some of these Wadis, and some irrigation activities are also sustained by harvested runoff water or groundwater extracted from adjacent alluvial aquifers attached to these Wadis. The topography of the state is dominated by highlands such as J. Marra in the north, Jebaal Dago' to the east of Nyala, Jebel Kas, Game' A'bu Agora to the northwest, and

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relatively high mountains at the west, around Hoferet En Nehas. The southern part of the state is characterized by flat sand sheets covering the country and relatively tall Qoz sands. The state population mostly settles at places where water is available. The size of the community determines the type of water source, which is determined by the topography, rainfall quantity, runoff volume, and groundwater occurrence. To identify the different types of water sources, it is necessary to consider the geological set-up in the state. The geology of South Darfur State is very simple in the northern part and up to Graida (120 Km. South Nyala) and Hofart En Nahas districts the Basement Complex covers most of the area. The Basement Complex rocks are shallow and covered by superficial wind deposits of sand sheets or Qoz sands. Along the seasonal watercourses, the shallow Basement Complex rocks are weathered, fractured, fissured, and covered by thin to considerable alluvial deposits. The thickness of the alluvial overburden differs due to the development of the Wadi and whether the Wadi is structurally controlled or not.

The process of identifying suitability maps for rainwater harvesting techniques (RWHT) involved five steps:

1. Collection of necessary data
2. Selection of RWHT
3. Identification and selection of appropriate criteria for each technique
4. Suitability classifications for each criterion
5. GIS application and map suitability development.

The methodology used to select sites for locating suitable water harvesting techniques in the study areas is shown in Figure 2.

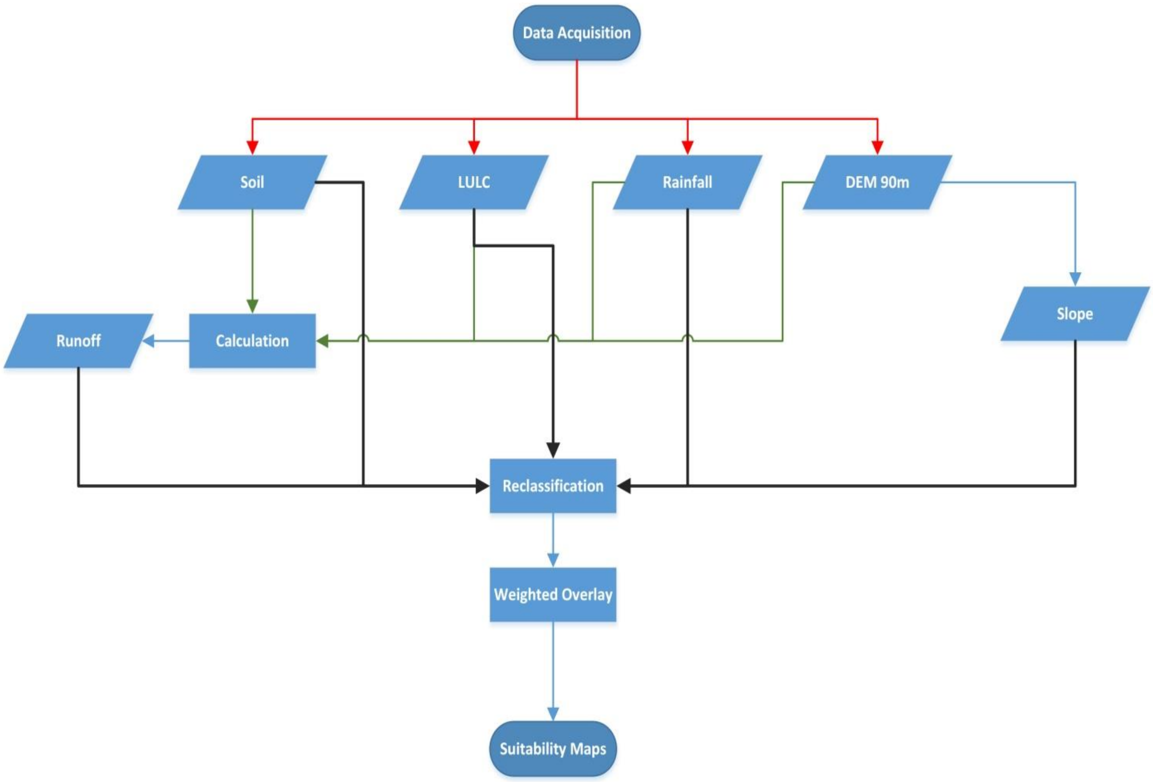

Figure 2: Flowchart of the overview of the research methodology

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To evaluate the suitability of this area for RHT, the data used here are:

The boundary data of the administrative districts of the study area (Polygon).

The remote sensing image of the study area was used to extract land cover types (Raster images, with 1 m resolution).

Digital elevation model data (DEM) of the study area to calculate the elevation, slope, catchment run off and flow path of the study area, and curve number (CN) (Raster images, 30 m resolution).

Point of Interest (POI) data of the study area for climate and soil parameters to was used to calculate the RWH selection indicators.

Input Maps: Figure 3 shows the GIS input maps representing the levels in the developed model for the suitability analysis. The long-term average annual precipitation for the entire (SDS) is shown in Figure 3f. The amount of precipitation varies greatly within the SDS. In particular, the northern parts of the SDS are much drier. Potential runoff, shown in the CN figure in Figure 3c, is low in areas with sandy loam soil in Figure 3b and very high in built-up areas of high rains in Figure 3f. Permanent crops, including arable crops and irrigated farming are found mainly in the regions with higher rainfall (Figure 3f). Pasture dominates in the southern parts of the SDS.

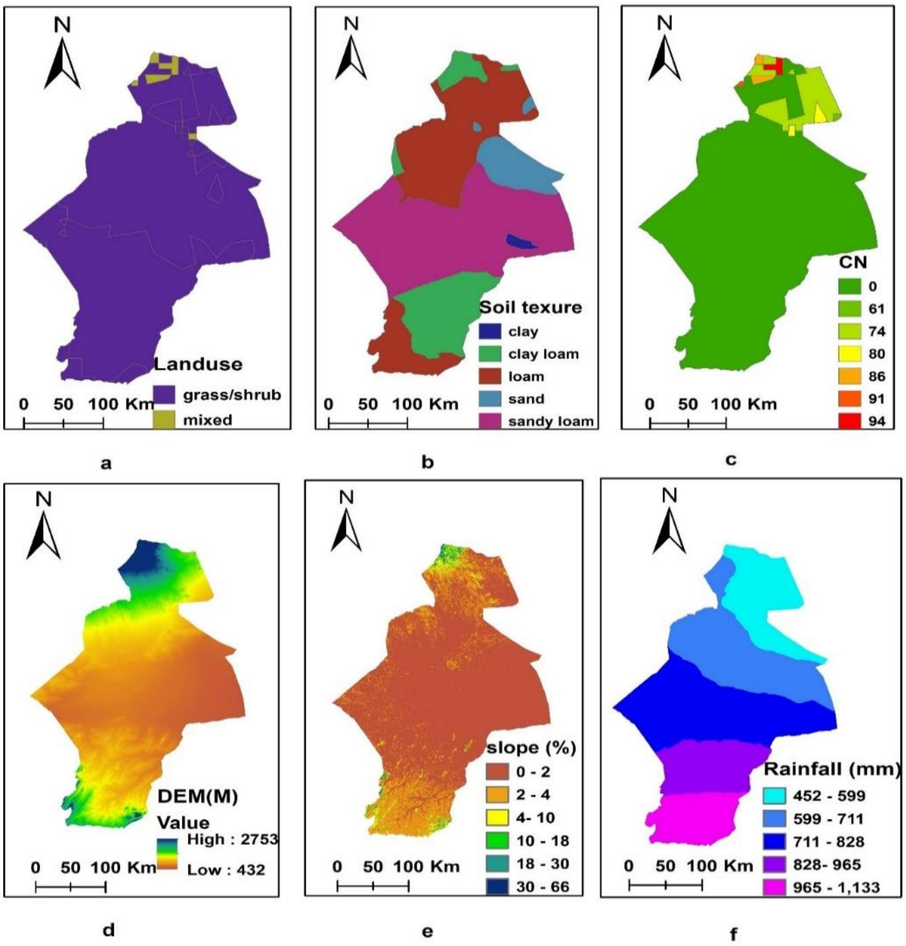

Figure 3: Input maps for the SDS: (a) land use (b), soil texture, (c) runoff curve number (d) dem, (e) slope and (f) rain fall.

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Slope Map: The slope is a significant parameter for identifying the best site for water harvesting to acquire the extreme storing volume in the channel (Ibrahim, Rasul et al. 2019). This parameter is determined by the terrain ratio, which denotes the ratio of the height difference between two points divided by the horizontal straight-line distance between them(Han 2003). The slope parameter influences the runoff, sedimentation ratio, recharge, surface water velocity, and the number of materials essential to creating dams (Malczewski 2004). The DEM with a 30 m resolution was used to generate the slope map, and the area was then divided into four classes (Figure 3)

Stream Order Map: The hydrological parameters from the spatial analysis tools were derived to produce the stream order map based on the DEM data. The main surface water is watershed. In the dry season, water gathering is used for human life, livestock, and other purposes. The arrangement of the stream is based on the linking of tributaries. The stream order refers to the hierarchical linking between the flow sections and allows the drainage basins to be classified according to their size. In addition, for mapping rainwater conservation streams, the order analysis is significant due to higher stream orders having lower permeability and infiltration.

Land Cover and Land Use: One of the key criteria for selecting suitable sites for water harvesting is the land cover and land use. The hydrological response of the river basins is affected by the land cover/use change and rainfall. Runoff feature of the watershed is under the influence of the land cover change. Land cover is associated with high runoff, generated by rainwater in a certain area due to higher infiltration, while low runoffs are associated with vegetation areas (Rida 2012). The study depends on the Landsat 8 image satellite to extract land use and land cover data with a 30 m spatial resolution. Supervised classifications with a maximum likelihood logarithm was used to assess the land cover/use map. Figure 3 assess the land cover/use map and demonstrates the land cover classification into only two main cover classes

Soil Types: The soil permeability is a significant parameter which controls the infiltration ratio and storage of water in the layers of the soil (Singh, Kumar et al. 2020). The soil textural class is determined through the percentages of sand, silt, and clay. The fine and medium textured soils are more suitable for rainwater harvesting, due to their ability to hold a higher content of water. The suitable soils for the water harvesting process have a higher capacity for water retention (Anschütz, Kome et al. 2003). The soils that have high clay content have a relatively higher runoff depth and do not permit more infiltration, whereas sand soils have lower runoff and higher infiltration. The soil map contains five different classes in the study area (Figure 3b).

Selecting RWHT: In this study the selection of possible and appropriate candidate of rainwater harvesting (RWH) technique is based on: First define those methods that meet the fundamental technical design requirements for assuring long-term implementation of the technique. Second, data were collected with respect to the most practiced RWHT in the study area and in other districts with similar climatic conditions and topography. Third, an overview of the critical values for climate, soil conditions, topography, and other variables affecting each RWHT was created and a pre-selection list for the RWHT was made. Finally, the pre-selected list was discussed with local experts, considering the already implemented RWHT. As a result, seven RWHTs were selected: runoff basin system, contour furrows, flood, flat, check dam, on-farm pond and terraces involve choosing criteria and decision options (Mburu 2008), (Rao, Annapurna et al. 2022), (Sethi, Jajoria et al.)

The Selection Criteria: The proposed selection criteria includes rainfall intensity surface runoff, land use, slope, and soil texture (Oweis, Prinz et al. 2001). Slope control the amount of runoff harvested and therefore the type of rainwater harvesting. Each rainwater harvesting requires certain amount of runoff and / or the amount of excess runoff it can handle without damage. Soil depth and soil texture determine the amount of water the soil profile can store and consequently the rooting depth. High

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water holding capacity is needed for survival of crops because rainfall is sporadic. Vegetation cover is indicator of the potential of land to support rainwater harvesting. According to Schillaci et al (Schillaci, Acutis et al. 2017) rainfall is a key selection criterion. Land use as an agronomy parameter, slope as a topography parameter, and soil texture as a soil parameter. In any RWH system, the amount and distribution of rainfall are essential factors in determining whether a specific RWHT is suitable or not in a particular location. In the study area the rainfall is characterized by high temporal and spatial variation (Melesse and Shih 2002). When designing rainwater harvesting systems, the catchment region should receive enough rainfall for storage for future use.

Discussions among a multi-disciplinary team of researchers (specialists in agronomy, water harvesting, range, hydrology, GIS, livestock, soil, land resource management, and socio-economic) resulted in some modifications of these criteria. For each criterion there were two ratings identified as the ''best'' and ''second best'' options. This was meant to provide more flexibility when determining the suitability of an intervention. For example, if the land is suitable for three different interventions, the land user could select one of them based on his or her preference and needs.

Following the rationale of AHP for water resources management, implemented before in the GIS environment it is possible to classify RWHT suitability by the following steps (Figure 4):

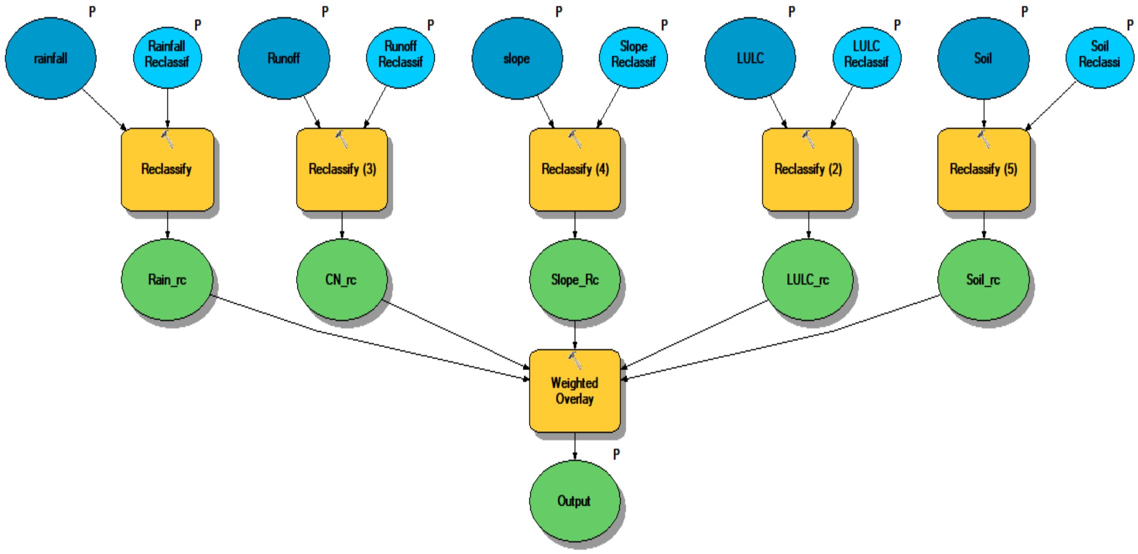

Figure 4: Conceptual flow chart for the selection process

Selection Criteria Weights: AHP is a method of multi-criteria decision – making technique (MCDA) is implemented within GIS, to define weights for the criteria. AHP was initially developed by Saaty (Saaty 2008). Several studies have been carried out for deriving weights of criteria for groundwater recharge (Longill et al, 2008, Rolland et al, 2013). The AHP can deal with inconsistent judgments (Saraf and Choudhury 1998) and (Saaty 2008)

The Pair-wise Comparison Matrices (PCMs) involves comparing all the possible pairs of criteria in order to determine which of all the criteria is of a higher priority. The AHP method is based upon the Construction of a series of PCMs, which compare all the criteria to one another. Saaty (Saaty 2008) suggests a scale from 1 to 9 (Table 1) for PCM elements. The value of 1 indicates that the criteria are equally important and a value of 9 indicates that the criterion under consideration is extremely

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important Compared to the other criteria. PCM includes a consistency check where judgments errors are identified and a consistency ratio is calculated. The three main stages used to make decisions based on PCM in the AHP method operations [24] [25] are:

- The determination of the important criteria in the problem (water harvesting sites).
- The assessment of the relative importance of each criterion to each other. This is usually done by experts using a scale from 1 to 9 (Rao, Annapurna et al. 2022)

The assessment of the consistency through pair-wise comparisons to assign the Consistency Ratio (CR). This stage involves: calculating the priority vector for a criterion, computing the principal Eigen value (λ), computing the consistency index (CI), determining the appropriate value of the random consistency ratio (RI) by Table 2, and 4) calculating CR. Max.

Table 1: Scales for the pair-wise comparisons method

Intensity of Importance	Definition	Explanation
1	Equal importance in a pair	Two criteria contribute equally to the objective
3	Moderate importance	Judgment and Experience slightly favors one criterion over another
5	Strong importance	Judgment and Experience strongly favors one criterion over another
7	Very strong importance	Judgment and Experience very strongly favors one criterion over another
9	Extreme importance	The evidence favoring one criterion over another is of highest possible validity
2,4,6,8	Intermediate values	When compromise is needed
Reciprocals	Values for inverse comparison	If criterion (i) had one of the above numbers assigned to it when compared with criterion (j), then (j) has the reciprocal value when compared with (i).

Table 2: Average random consistency indices (RI) for different number of criteria

Number of criteria (N)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Random consistency indices (RI)	0.0	0.0	0.68	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.54	1.56	1.57	1.59

Selection of the Local Experts: Upon definition of selection criteria a group of five experts were selected and interviewed to give criteria weight (based on the scale of 1 – 9 as sown in table 2). The selection of the experts was based on their experience, and knowledge of study area. The background of the selected experts covered the fields of geology, hydrogeology, civil engineering (water resources), agriculture, groundwater, and Geographic Information System (GIS). The interviews were conducted face to face to assess the relative importance of each individual criterion with its subclasses and to assign weights to each of the candidate WHTs. Criterion Suitability Classifications: In this step, the different values within the different datasets were converted into a common suitability scale using GIS and MCA. Due to the different measures and weights for the different criteria, each of the five criteria was first classified (Rida 2012) and (Malczewski 2004)). The weight for each criterion was determined after assigning scores using the (AHP) and the pair-wise comparison matrix (Giap, Yi et al. 2003). When comparing and scoring two criteria, a continuous 9-point scale is used, with odd numbers 1, 3, 5, 7, and 9 representing the range of suitability (not suitable–very suitable) of the criteria compared to each other. The scores were assigned and adjusted based on active discussions with local

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experts and engineers, as well as on information from previous scientific work. The (PCM) was applied within the (AHP) to check the Consistency ratio (CR) and to identify the final weights for each criterion. CR was calculated for all the acquired experts' opinions to check if it is less than or equal to 0.1, thereby to check the suitability of each pair-wise comparison. GIS Application and Maps Suitability Development: In creating the datasets, the DEM and rainfall station data required additional analysis to derive the input data maps for slope and precipitation. Based on the suitability scale, a new scaled map was created for each input layer. The Spatial Analyst module of Arc GIS 10.2 was used to determine suitability by reclassifying the criteria layers and using the raster calculation tool. The final step is to combine the converted output layers of annual perception, land use, slope, soil texture, and CN. For each RWHT, each criterion was classified as a numerical value and assigned a suitability value. Then, the suitability values were classified into four groups: low (<20), moderate (20–29), high (30–39), and very high (>39). Figure suitability map for each RWHT. A Model Builder in Arc GIS 10.5 was established for generating a suitability model, which included steps for calculating the suitability score for each RWH

Table 3: The pair-wise comparison matrix of expert options

Criteria	Rainfall intensity	Surface runoff	Land use	Slope	Soil texture
Rainfall intensity	1	2	6	2	4
Surface runoff,	0.5	1	4	1	2
Land use,	0.16	0.25	1	0.25	0.5
Slope,	0.5	1	4	1	2
Soil texture	0.25	0.5	2	0.5	1

Five physical criteria were used in the research for selecting the suitable sites for the water harvesting recharge are: (rainfall intensity, Surface water runoff, land use, slope, and soil texture). Weights and ratings were given to each individual criterion The Weighted Linear Combination (WLC) technique was used to identify the potential sites for water harvesting in the study area by integrating these physical criteria. The process of implementing the After the collection of all criteria, determination of weight of each criterion and combining these weights, WLC technique includes standardizing the suitability maps, assigning weights of relative importance to the suitability maps, then combining the weights and the standardized suitability maps and obtaining a final suitability map. In doing this all the generated thematic layers were integrated in Arc GIS ® to derive a map depicting the suitable areas for the water harvesting of the study area. The total weight of each map of the final integrated layer was computed using Equation 1:

$$Si= (RIw * RIr) + (ROw * ROr) + (LUw\ LUr) + (SLw * SLr) +(STw\ STr) \quad (1)$$

Where, ‘Si’ is the water harvesting index, which is a dimensionless number that identifies the suitable sites for the water harvesting in the area. “w” represents the weight of each criterion, and “r” represents the rating of each criterion namely: (rainfall intensity (RI) , runoff (RO), land use (LU), slope (SL) , and soil texture (ST)). As shown in Table 4, the five GIS layers representing the physical criteria were subjected to a GIS analysis to select the optimum sites for the water harvesting in the study area based on these criteria. All maps, the following spatial data techniques were used: Updating attribute tables; Converted to a raster format; Slope derivation; Raster reclassification; Raster calculation (integrated to produce the optimum sites for the water harvesting within the study area. According to Equation (1), the study area was classified into five classes in terms of the suitability for the water harvesting technique including: very low suitability, low suitability moderately suitable, high suitability, and very high suitability for water harvesting. These thematic layers were integrated to generate a water harvesting suitability map of the study area as shown in Figure 3. The Boolean

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technique was then used in classifying study area to eliminate those sites which are not suitable for the water harvesting.

Table 4: The rating of the five criteria selected based on literature review and weights

Criteria		Techniques						
	Classes	Flat	Furrow	Basin	terraces	Dam	Pond	Flood
Rain falls (mm)	452-500	9	3	5	7	3	3	3
	501-800	7	9	5	9	5	5	5
	801-1000	5	5	3	5	7	7	9
	1001-1133	3	1	1	1	9	9	7
Land use	Gross/shrub	5	5	3	3	3	3	3
	Mixed	3	3	5	5	5	7	5
Runoff (CN)	0 – 60	3	3	3	1	3	3	3
	61-74	7	5	7	3	5	5	5
	75-86	5	9	5	7	7	7	9
	87-90	3	3	3	9	7	7	5
	> 90	1	1	1	5	9	9	3
	Flat (0-2)	9	7	5	5	3	3	3
	Gentile (2-5)	7	9	7	7	5	7	5
Slope %	Moderate (5-10)	5	5	5	9	7	9	7
	Rolling (10-15)	1	3	5	3	9	5	5
	Hilly (15-30)	1	1	3	1	1	1	1
	Speed>30	1	1	1	1	1	1	1
Soil texture	Clay	7	7	5	9	9	9	7
	Clay Loam	9	5	5	7	7	7	9
	Loam	5	9	7	5	5	5	5
	Sandy loam	3	3	3	3	3	3	3
	Sandy	1	1	1	1	1	1	1

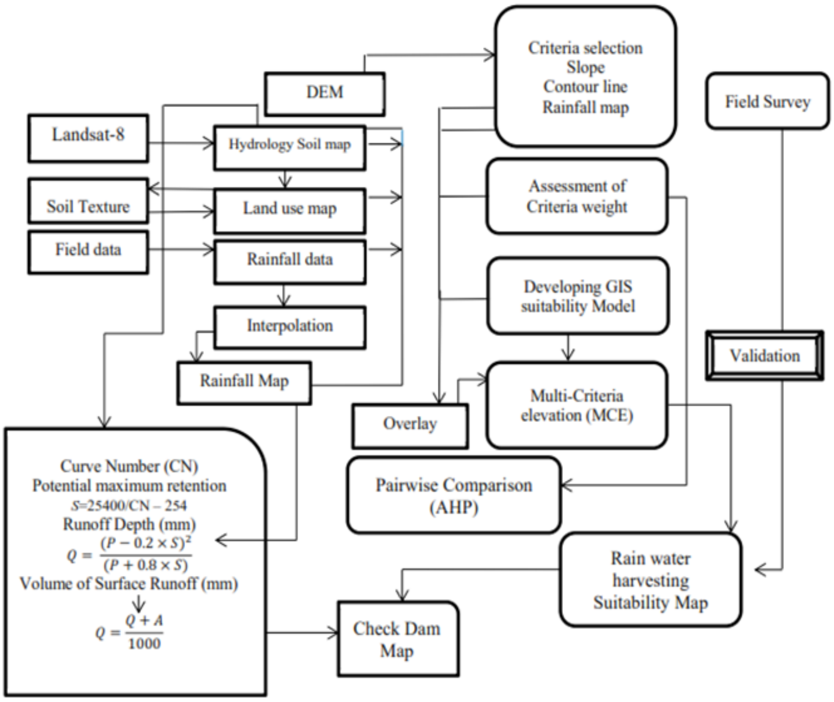

Figure 5: Flowchart for generation rain water harvesting mapping, (Qv is the volume of surface runoff (mm 3), Q is the runoff depth (mm) and A is the basin area (km2)

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RESULTS AND DISCUSSION

Water Harvesting Suitability Mapping: The maps identified by the spatial analyst module shows the suitability on a scale from red (not suitable) via yellow (moderate suitable) to green (very high suitable), based on the five selected criteria. Figure -3- shows an integrated suitability map created with specific analysis properties in Arc GIS 10.5. Each RWHT has been assigned a specific color to indicate its high suitability for a specific area in SDS. The WLC method was then used to integrate the generated suitability maps of the individual physical criterion in to a one suitability map for water harvesting in the study area. In addition, the Boolean method was used to eliminate the sites that are not suitable for water harvesting and generate an unsuitability map. The resultant maps (Figure 3) from the physical criteria, shown in Figure 1

Suitability Score for Each Criterion for the RWHT: All seven selected rainwater harvesting techniques (RWHTs) were assigned a suitability scale. All layers were re-classified according to their suitability with a specific score, as shown in Table 5. The suitability ratings and criteria selection were the result of several discussions with local experts and engineers with experience in developing RWHT. The ratings were updated and modified several times depending on the previous studies to avoid discrepancies in the allocation of points (Abdo and Salih 2011). The Potential of RWHT: Figure 6 shows potential maps for different types of RWHT. The maps identified by the spatial analyst module show the suitability on a scale from red (not suitable) via yellow (moderate suitable) to green (very high suitable) based on the five selected criteria. To obtain an overview of the suitability assessment for all selected techniques together, Figure 7 shows an integrated suitability map created with specific analysis properties in Arc GIS 10.5. Each RWHT has been assigned a specific color to indicate its high suitability for a specific area in SDS. The map shows a large discrepancy in the amount of land suitable for the different RWHTs.

From the maps in Figure 6 and the integrated map in Figure 3, it is clear that the different RWHTs have different suitability in SDS. Each RWHT has its own suitability map, which reflects the technical requirements for that technique and is influenced by the criterion. Runoff basins: Runoff basins are most suitable on the southern eastern borders of SDS in the relatively shallow parts nearby Bahr El Arab, and the soil is mostly clay to clay loam. Map statistics show that more than 70% of the area of SDS is not suitable for this technique. The Debla hilly sandy area shows no suitability for Runoff basins Contour furrows: Seventy percent of the area of SDS is very suitable for the contour furrows technique. Most of the well-suited sites are in the northern parts and the mid area with cropland and pasture. The technique suits areas of moderate precipitation (more than 250 mm). Flat: Suitable to flat areas of high to moderate rain fall in the southern, mid parts of SDS, It suits some areas of light soils and moderate rain in north east boundaries to grow grasses as pasture

Farm pond: As for the farm pond, the areas with high suitability for this technique are mainly located in the Northwest area (Jabal Mara area) with 10% of the area with moderate slopes and clay soil being very suitable for this technique. Highly suitable areas for implementing eyebrow terraces are located mainly on the southeastern borders and at the fringes of Bahar El Arab. Check dams: It should be noted that according to this analysis, about 40% of the area of SDS, which is mainly lies in the south and southeast is highly suitable for the construction of check dams. The technique shows relatively low or no suitability in the north and mid areas of less intensity of surface streams. Terraces: Highly suitable areas for implementing eyebrow terraces are located mainly on the northern and mid areas. It is not suitable to southeastern borders with high rains. Statistics showed that about 60% of the area of SDS is moderately suitable for this technique. This can be explained by the fact that this technique is less suitable for high rain fall that wash out the terraces. Although Bench terraces are too expensive, they are technically very suitable to the hilly north areas of Jebal Mara. Contour terraces are less suitable for mechanized cropping operations because of their irregular shape. Nevertheless, this

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technique dominates the areas of moderate rain fall and clay soil in the north and mid parts of SDS. Flood: About 20% of the total area of SDS is very suitable for the flood technique in the areas occupied by small streams "Khors" in the southern pars and nearby Bahr El Arab River. Some flood water harvesting can be practiced in Jabal Mara areas. The unsuitable areas are vast (more than 70% of total SDS area) is mainly in the mid and the northwest parts where the soil texture is mainly classified as clay loam, as the infiltration rate in the catchment area of the flooding areas is an important factor for suitability. Therefore, the area with high infiltration rate, moderate to medium rain fall and low CN Value shows low suitability for the flooding techniques.

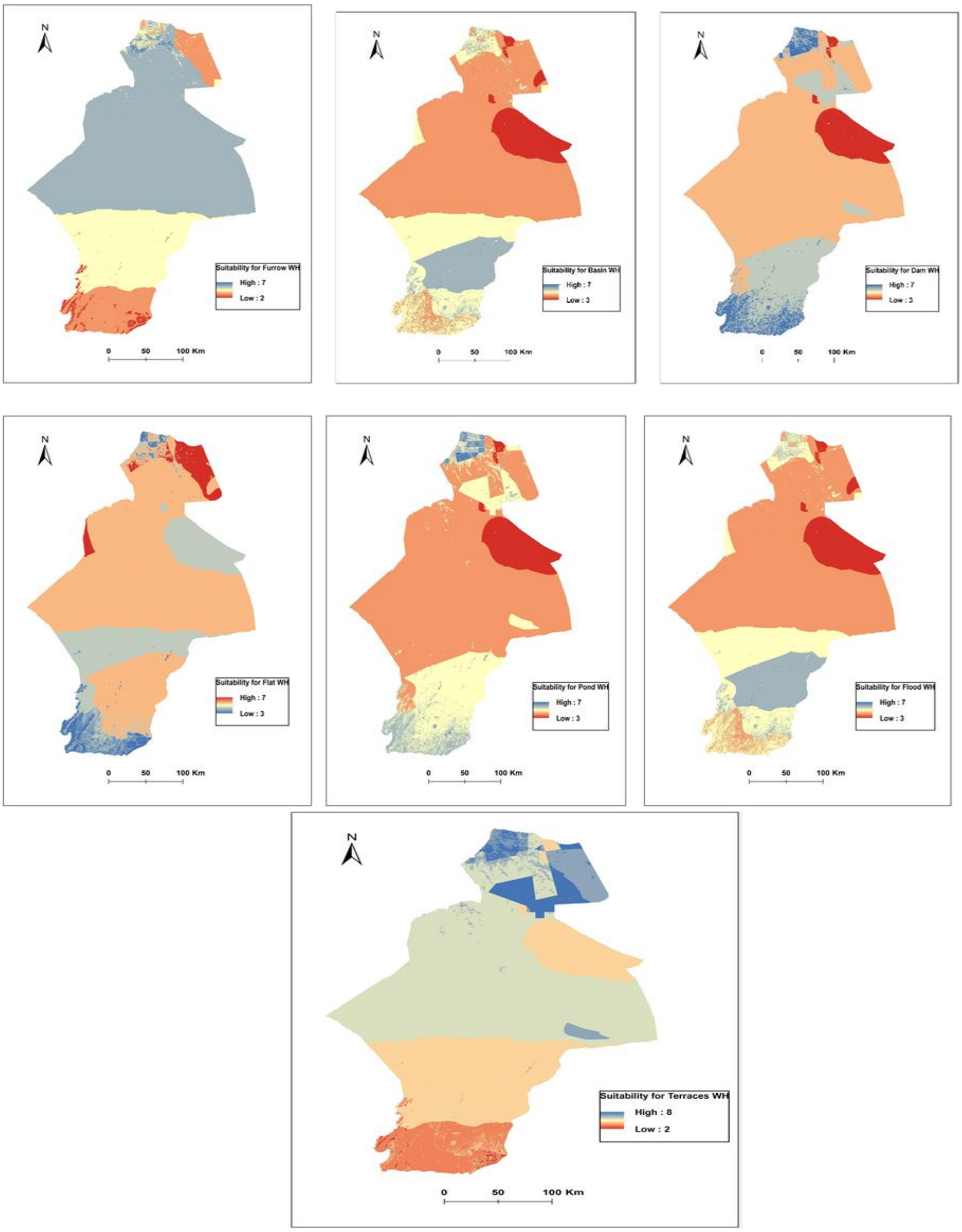

Figure 5: Suitability maps for different types of RWHT in the SDS, Sudan, based on soil type, slope, rainfall, land use, and curved number

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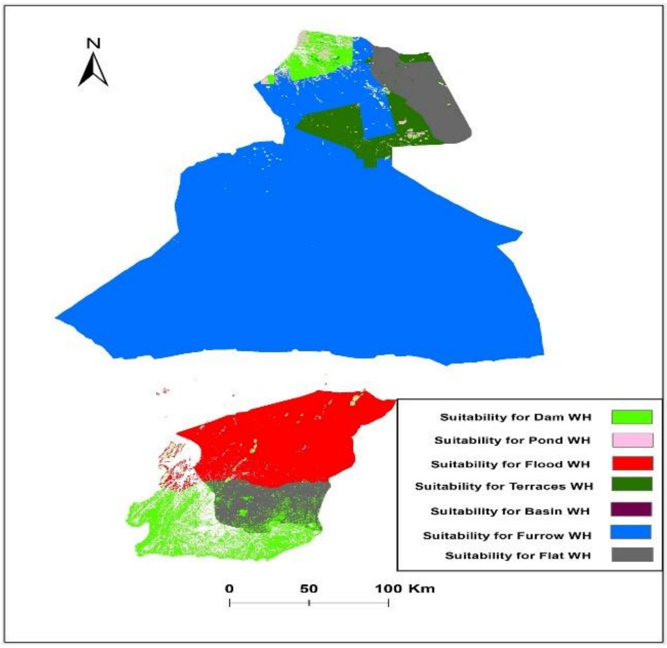

Figure 6: Integrated suitability map of all the seven RWHTS for the SDS, Sudan

The relatively high suitability scores for these RWH techniques do not mean that these are the best solutions for farmers, as socioeconomic, political, and cultural aspects were not considered in this analysis. Bench terraces, for example, are too expensive in most cases due to high labor costs. Eyebrow terraces are less suitable for mechanized cropping operations because of their irregular shape. Nevertheless, this approach can help farmers and decision makers in the initial selection of RWHTs suitable for their region.

CONCLUSIONS AND RECOMMENDATIONS

The study objective is to develop a methodology for identifying the suitability for different rainwater harvesting techniques using participatory GIS approach and Analytical Hierarchy Procedure (AHP). The main biophysical parameters used to assess the suitability for rainwater harvesting were slope, soil depth, soil texture, and stoniness. Criteria for each parameter were integrated and a suitability map was produced using raster-based and classification-based analysis. A suitability model based on GIS, created with Model Builder in Arc GIS 10.5 and Analytical Hierarchy Procedure (AHP), was used to identify potential RWHTs. A set of criteria (rainfall, runoff, slope, land use and soil texture) were included in the suitability model. The study concluded that the following steps should be conducted to ensure validated outcomes: 1) Surveying the suitable sites to establish if these sites are not occupied with other land uses of high socio- economic values. This will help in preventing the selection of such sites that have not been known to the researcher when conducting the selection analysis. 2) Geophysical investigation to study the subsurface layers within the study area. This will help in determining whether these layers are suitable to establish a water harvesting structures above these layers and. 3) Soil sampling from various locations within the study area to test the clay contents. This will help in validating the suitability of soils within the study area to establish water harvesting.

According to the results of this study, this research technique provides an initial meaningful screening of broad areas and is an extremely useful tool for assisting in the development and implementation of a rainwater harvesting (RWHT) project, especially in arid and semi-arid environments. Arc GIS 10.5 has proven to be an extremely useful, versatile, time-saving and cost-effective tool, in this study, for integrating information to identify ideal locations for different RWHT in vast regions. Agricultural

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engineers, hydrologists, decision makers, and planners will benefit from the suitability map as it will allow them to easily identify which rainwater harvesting technique (RWHT) to use in sites with RWH potential. The quality and accuracy of the data, as well as the way the data were sourced, processed, and produced, were all factors in the quality of the map.

To verify the applicability of the model, it needs to be calibrated and tested in different regions and with different RWHTs. As the suitability ratings have a major impact on the maps of RWHT suitability, a validation study or pilot project is recommended to ensure the margin of error (if any) in determining the preferences for each RWHT. Socio-economic criteria such as investment and maintenance costs and labor input may also be important for water harvesting. Therefore, socio-economic suitability for different RWHTs needs to be explored and included in the assessment process. These ideas will improve the realization of the model and broaden the scope of this methodology. For improving crop productivity and to secure food for the increasing population in SDS this study generated a planning map to identify the suitable WHT sites at for the different geographical parts of the state.

From the outcome of this study, it is recommended that runoff basin systems are suitable to be used in the southwest high rain parts of SDS and it is the most suitable technique for about 30% of the area of SDS. Contour furrows, flat and terraces techniques are highly suitable for 70% of the state area with moderate rain fall to grow pasture. Flooding technique is not recommended except in the highly rain fall southern areas near by Bahr El Arab. The check dam and pond techniques are suitable in the middle to the southern areas that occupied by small surface streams running towards Bahr El Arab. Farm ponds or flooding techniques are not suitable for Debla hilly area or the northern areas with low rain fall. For Jabal Mara area it is recommended to employ bench terraces. Finally, this approach can assist decision makers in the efficient planning of the water resources management to ensure a sustainable development of the water in arid dry areas suffering from water shortages.

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