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Site Suitability Analysis for *In Situ* Rainwater Harvesting Structures Using Remote Sensing and GIS in Sheikan Locality, Sudan.

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Abstract: The study was conducted in Sheikan locality in 2017 to identify appropriate sites for Rainwater Harvesting (RWH). A systematic identification of the appropriate sites for different RWH structures may contribute to a better success of crop production in such areas. One approach used to adapt to climate change is *in situ* water harvesting for improved crop yields in Sheikan locality, Sudan. The main objective of this study was to determine the suitable sites for *in situ* water harvesting structures in the face of climate change through the use of GIS and Remote Sensing techniques in Algabal and Wad Albaga areas of Sheikan locality. A GIS based model has been developed to generate suitability maps for *In-situ* RWH using multi criteria evaluation. Five suitability criteria (soil texture, runoff depth, rainfall surplus, land cover, and slope) were identified for *in situ* RWH and for each criterion, five suitability levels were chosen (Excellent, Good, Moderate, Poor, and Unsuitable). Weights were assigned to the criteria based on their relative importance for RWH using an analytical hierarchy process (AHP).Using QGIS and ArcGIS software, all criterion maps and suitability map of the study area were prepared. Consequently, from the obtained suitability map Wad Albaga location (semi-circular bunds) falls in good portion (844 km^2)

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which represents 46.04%**,**whereas Algabal location (terraces bunds) lies in themoderate class (341 km^2) with 18.6%.However, Algabal location was considered as moderate site which was attributed to the soil texture which was sandy clay soil and was ranked as the second most important class compared to Wad Albaga location which was sandy clay loam soil. The obtained suitability map facilitates the identification of sites where *in situ* RWH structures can be realized. The study concluded that identifying suitable sites using GIS is cost-effective and time-saving method to discover the most appropriate sites for RWH.

Keywords: Rainwater Harvesting, GIS, North Kordofan, Sudan.

INTRODUCTION

Climate change has resulted in increased vulnerability of smallholder farmers in marginal areas of Sudan where there is limited capacity to adapt to a changing climate. One approach that will be used to adapt to changing climate is in-field water harvesting for improved crop yields in the semi- arid regions of Sudan (Nyamadzawo *et al.*, 2013).

In situ rainwater harvesting, involves the use of methods that increase the amount of water stored in the soil profile by trapping or holding the rain where it falls. This involves small movements of rainwater as surface runoff, in order to concentrate the water where it is required (Mudatenguha *et al.*, 2014).

In situ water harvesting retains moisture, through structures that convey the runoff produced nearby and hold water long enough to allow it to infiltrate. Improved in-field water harvesting reduces crop moisture stress and thus can result in improved crop yields. Improved water harvesting may result in improved crop yields, food security and livelihood among households (Nyamadzawo *et al.*, 2013).

The main consequences of climate change in arid lands of Sudan will be a decrease of agriculture, rangeland and forest productivity, biodiversity, soil organic matter and fertility. This will worsen poverty and food insecurity. Populations will be forced to migrate (Malagnoux, 2007).

Water harvesting is nothing new but a revival of old techniques that have received little attention since the modernization of agriculture in the 1940s (Nyamadzawo *et al.*, 2013). Due to the flexibility and adaptability to a very wide range of conditions, these techniques are now being used and practiced in the wettest and driest regions and in the richest and poorest societies of the world for many uses, including crop production (Sendanayake, 2016).

In the late years of the 1970s and 80s, adoption of soil and water conservation techniques was greatly affected by the political environment and this resulted in poor uptake. Most of the water harvesting innovations and crop improvement techniques which were promoted in the 1990s' improved crop yields in marginal areas but were poorly adopted by farmers because they are labour intensive (Nyamadzawo *et al.*, 2013).

The region is a rain-fed area with insufficient and uneven precipitation due to the erratic nature; therefore rainfall in this region is unpredictable both in amount and time. There is a water scarcity throughout the region and subject to various hydrological constraints particularly within the communities who are reliant on rain-fed agriculture. This area suffered from the increasing frequency and severity of drought(Hassan Elnour, 2010).

GIS techniques are widely used for planning, development, and management of natural resources at regional, national, and international levels. They have been applied to the assessment of several water related environmental challenges such as soil erosion, degradation of land by water logging, ground and surface water contamination, and ecosystem changes (Weerasinghe *et al.*, 2011).

Past experiences show that rainwater harvesting structures are an innovative approach for the integrated water resources management and sustainable development of semi-arid areas (Wani *et al.*, 2005).

The objective of this study was to determine the suitable sites for *in situ* water harvesting structures in the face of climate change through the use of GIS and Remote Sensing techniques in Elgabal and Wad Albaga areas of Sheikan locality in Sudan.

MATERIAL AND METHODS

The selected study area is located in North Kordofan State, which is one of the most vulnerable areas in the country affected with desertification processes. It is located in central Sudan between latitudes 9° 30' and 16° 24' N and longitudes 27° to 32° E.

The rainy season is from June to October with the highest precipitation generally occurring in August. The annual rainfall range is from 250 to 400 mm. Soil of the study was classified as “sandy clay, clay loam, loam, sand, sandy clay loam, and sandy loam”.

Soil data collection

Soil data were accessed from the Agricultural Research Corporation (ARC), Department of Land Evaluation. This department has conducted soil survey for the whole region using an Auger tools as well as from soil profiles. GPS tool was used to record the exact coordinates for each soil sample. Hence, soil data of the two locations were used to represents the two existing rainwater harvesting structures (semicircular bunds and terraces). Soil texture map for the study area was then created to be used in making the suitability map.

RWH potential mapping approaches

The identification of suitable sites of rainwater harvesting techniques is a multi-objective and multi-criteria problem. This study was trying to map potential sites for both types of RWH structures (semi-circular and terraces bunds). Five suitability criteria for these structures war identified.

Criteria selection and assessment of the suitability level

Five criteria were selected for the identification of the potential sites for both *in situ* RWH interventions: “Soil texture, Runoff depth, Rainfall surplus, Land cover, and the Slope”. The suitability map was converted into comparable units due to the different scales of each criterion. Thus the criteria map was re-classified into five comparable units as follow: Excellent, Good, Moderate, Poor, and Unsuitable.

Soil texture*:* Clay soils have low permeability (high hydraulic resistance) and therefore have the capacity to hold the harvested water, they are considered as best soils for water storage (Sharma and Chanjta, 2017).Bulcock and Jewitt (2013) considered medium-textured loamy soil the most suitable for agricultural production.

Runoff depth*:* Runoff depth is considered an important parameter for water harvesting and proper watershed management (Rajbanshi, 2016).Runoff depth is calculated using the CN (Curve Number) based on hydrologic soil group (HSG) (A, B, C, and D), land use/land cover, treatment classes, hydrologic surface conditions and the antecedent moisture conditions.

Table 1: Description of the generic conditions for soil classification(according to the CN method) (USDA, 1988)

A	Low overland flow potential. Minimum infiltration capacity when wetted >0.76 cm/hour. Deep well to excessively drained sands. E.g. sand, loamy sand, or sandy loam.
B	Moderate minimum infiltration capacity when wetted 0.38 to 0.76cm/hour. Moderately deep to deep, moderately to well drained, moderately fine to moderately coarse grained (e.g. silt or loam).
C	Low minimum infiltration capacity when thoroughly wetted 0.13 to 0.38 cm/hour or soils with impeding layer fragipan (e.g. sandy clay loam).
D	High overland flow potential. Very low minimum infiltration capacity when wetted< 0.13 cm/hour. Clay soils with swelling potential, soils with permanent high water table, soils with clay near the surface, or shallow soils over impervious bedrock. E.g. clay loam, silt clay loam, sandy clay, silty clay, or clay.

Rainfall surplus*:* Rainfall surplus is used in this study to investigate the effect of the magnitude of the harvestable rainfall on site suitability of RWH. The rainfall surplus is therefore considered as criterion to account for the spatial distribution of harvestable runoff availability (Ketsela, 2009).

Land cover: This study was mainly focused on *in situ* rainwater harvesting structures for agricultural activities. The study uses land cover/or use as an important indicator and one criterion for selection of suitable sites of *in situ* RWH.

Slope: Kadam *et al.* (2012) indicated that, study areas which falls under very gentle to gentle slope class (Low and Medium surface runoff) indicate water retention for longer time and thus enhance the chance of infiltration and recharge.

Weighted Linear Combination (WLC) procedures

After selecting factors that influence the identification of the best sites, WLC was carried out. WLC comprehends some steps;

Reclassification: Reclassification is often used to simplify or change the interpretation of raster data by changing a single value to a new value. Each factor has been divided into classes and each class has been attributed a weight from 1 to n(n=number of classes). Weight 1 has been attributed to the class considered less suitable (Laurita, 2015).

Normalization: Once obtaining the five reclassified maps, it has been necessary to normalize the data. With normalization, it means the simplest case: adjusting values measured on different scales to a notionally common scale. This was easily done with QGIS Raster calculator, applying the formula: (Raster Value−MinValue) / (Max Value−Min Value). The five maps of this study were obtained using the procedures, all reported on a common scale of values, from 0 to 1 (Laurita, 2015).

Weighted Linear Combination (WLC): The performance of this method requires the existence of two possible procedures: Ranking and Pair-wise comparison. Factors are ordered on the base of their importance so as to be ranked accordingly (1 = the most important, 2 = the second one, etc.); the ranking is then converted in numerical values from 0 to 1 so that the sum is 1.To minimize the subjective aspects it has been decided to perform WLC through Pair-wise comparison, utilizing the Analytic Hierarchy Process (AHP) algorithm (Argyriou *et al.*, 2015).

Analytic Hierarchy Process (AHP*):* AHP is a multi-criteria decision-making approach. AHP is one of a GIS based MCDM (Multi-criteria Decision Making) that combines and transforms spatial data (input) into a result decision (output) (Feizizadeh *et al.*, 2014).The rating between two criteria is provided on a 9-point continuous scale (Figure 4) ranging from extremely less important to extremely more important. The comparison will be done for every possible pairing of criteria and the rating is entered into a pair-wise comparison matrix. Through this process each factor is rated for its importance relative to every other factor using a 9-point reciprocal scale (i.e. if 7 represents substantially more important, 1/7 would indicate substantially less important).

Saaty (1990) noticed that the process will include the structuring of factors that are selected in a hierarchy starting from the overall aim to criteria, sub-criteria, and alternatives in successive levels.

Saaty (2008) reported four steps as key factors in undertaking AHP in an organized method in order to make a decision over alternative as following: “Definition of the issue to be considered, Identifying the goal, Developing a pair-wise comparison matrix, and Weight priorities for each element”.

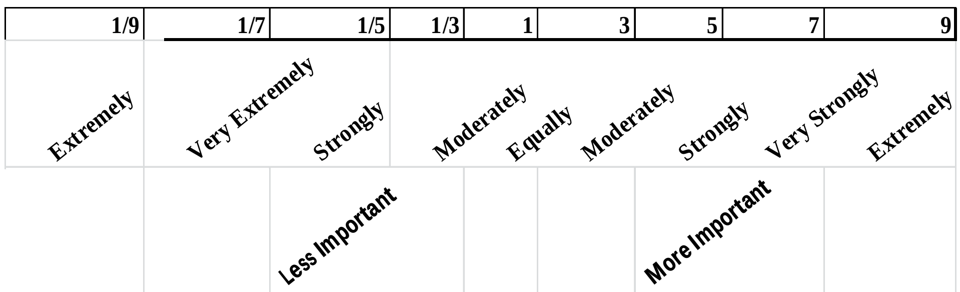

Figure 1: The Continuous Rating Scale developed by (Saaty, 1977)

GIS Analysis: All the processing in finding RWH suitability map has been implemented in a suitability model developed in QGIS 2.6.1 and ArcGIS 10.2.2

The suitability model generates suitability maps for RWH by integrating different inputs criteria maps using Weighted Overlay Process (WOP) also known as Multi-Criteria Evaluation (MCE). MCE was achieved by WLC wherein continuous criteria (factors) are standardized to a common numeric range, and then combined by means of a weighted average. With WLC, criteria were combined by applying a weight to each followed by a summation of the results to yield a suitability map using the following equation:

$$S = \sum Wi \,.\, Xi$$

Where S = suitability
wi = weight of factor i
xi = criterion score of factor i

RESULTS AND DISCUSSION

Analysis of the criteria maps of the study area

Soil texture map*:* Soil data were collected by the Agricultural Research Corporation, Department of Land Evaluation using GPS tools. Soil profiles were also dug for better details information. The soil map of the study area was then developed using the collected and analyzed soil texture data. This was reclassified into five numerical categories (classes) namely sand (rank 1), sandy clay (rank 4), sandy clay loam (rank 5), and sandy loam (rank 3).Wad Albaga ranked the highest site which was sandy clay loam, while Algabal was sandy clay and ranked as the fourth which is also good for *in situ* RWH (Figure).

Table 2: Suitability rank for soil texture for both structures (from Ketsela, 2009 modified)

No	Texture classes	Ranking classes
1	Sandy clay	4
2	Clay loam	4
3	Loam	5
5	Sand	1
6	Sandy clay loam	5
7	Sandy loam	3

This soil layer was rasterized using QGIS software and was considered as the first criterion in the AHP model. These findings are in line with Ketsela (2009) who demonstrated that the loamy soils are most suitable for in-situ RWH whereas clay soils are less suitable because of their low infiltration capacity and risk of water logging.

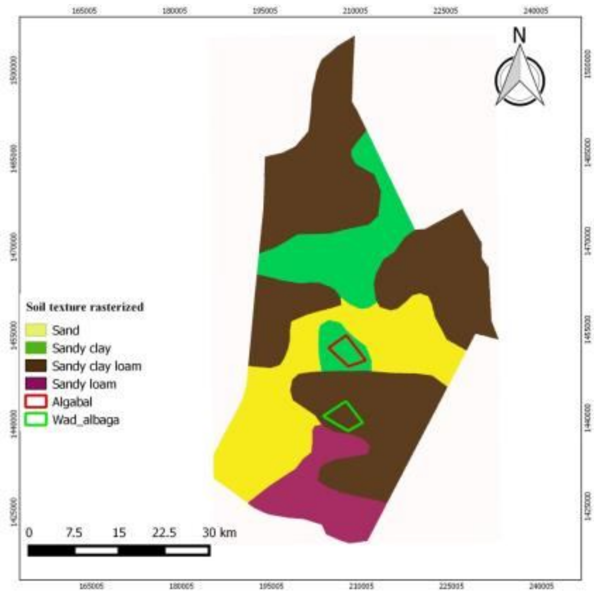

Figure 2: Soil texture map of the study area

Runoff depth map*:* Runoff depth is calculated using the CN (Curve Number) combined with CN-extension in ArcGIS, based on hydrologic soil group (HSG), land use/Land cover, treatment classes, hydrologic surface conditions and the antecedent moisture conditions. Runoff depth is considered to be an important factor when identifying the potential sites for in-situ water harvesting structures because it shows how deep the water to be harvested within the *in situ* structures. Therefore, the runoff depth criterion was considered to be important parameter in the model of AHP when identifying suitable sites for *in situ* water harvesting. This result is matches the findings of Rajbanshi (2016) who reported that the accurate estimation of runoff depth and volume is an important task for proper watershed management.

This map layer was then rasterized and reclassified as 0-19 mm (rank 1), 20-24 mm (rank 2), 25-26 mm (rank 3), 27-29 mm (rank 4), and 30-33mm (rank 5). Both locations were in the highest rank (rank5) with 30-33mm of runoff depth (Figure).

Table 3: Suitability rank for runoff depth of the region

No	Runoff Depth(mm)	Description	Ranking Classes
1	21-25	Very deep	5
2	17-20	Deep	4
3	12-16	Moderately deep	3
4	8-11	Shallow	2
5	0-7	Very shallow	1

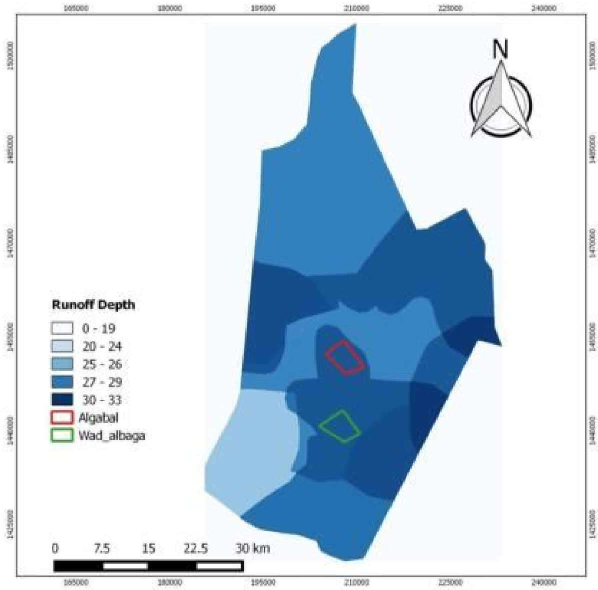

Figure 3: Runoff depth map of the study area

Rainfall Surplus map: The rainfall surplus map was generated by interpolating rainfall surplus values. The values were calculated by subtracting evapotranspiration from precipitation (P-ET) using data of 12 meteorological stations (2007-2016) of the whole region in and near the study area. The accumulated rainfall surplus was calculated by adding the positive values of the difference (P-ET) starting from rainy season. This rainfall surplus map was then put as the third criteria in the AHP model.

The calculated values were interpolated using the multilevel b-spline interpolation in QGIS. The new data were clipped to the whole region of North Kordofan State. The rainfall surplus map comprises five classes as indicated in Table5 below. Wad Albaga site has the large surplus and ranked as highest (rank5) in terms of importance with 42- 53mm, whereas Algabal site scored rank 4 which represents 32-41mm (Figure). As results, these rankings are similar to the study that was carried out in Ethiopia by Ketsela (2009) who reported that high suitability rank was given for areas with large rainfall surplus as it ensures the availability of runoff to be harvested.

Table 4: Suitability rank for rainfall surplus of the region (Ketsela, 2009.modified)

No	Rainfall surplus values (mm)	Description	Ranking Classes
1	0-1	Very large deficit	1
2	2-22	Large deficit	2
3	23-40	Medium deficit	3
4	41-60	Small surplus	4
5	61-80	Large surplus	5

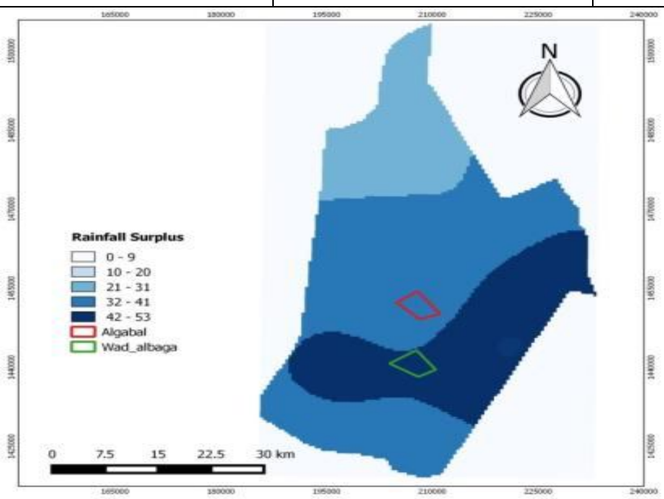

Figure 4: Rainfall surplus map of the study area

Land cover map: This was developed using Landsat 8 year 2017. This layer was digitized using QGIS software. This victor layer was then rasterized and reclassified into five classes as follow: cultivated land weight5, shrubs and grass land weight4, bare land weight3, forest and tree plantation weight2, and water bodies and artificial surfaces weight1 as restricted. As result, both locations were assigned within the highest class which is cultivated land (Figure).

Table 5: Suitability rank for land cover of the region (from Ketsela (2009) modified and Mahmoud and Alazba (2014))

No	**Land cover types**	**Ranking Classes**
1	Bare land	3
2	Cultivated land	5
3	Forest & tree plantation	2
4	Shrub and grass lands	4
5	Water bodies & artificial surfaces	(Restricted) 1

This study matches the case study of Mahmoud and Alazba (2014) who stated that as this study focuses on *in situ* water harvesting techniques for improving the environmental situation, the land cover and land use were employed as criteria to identify potential areas for *in situ*.

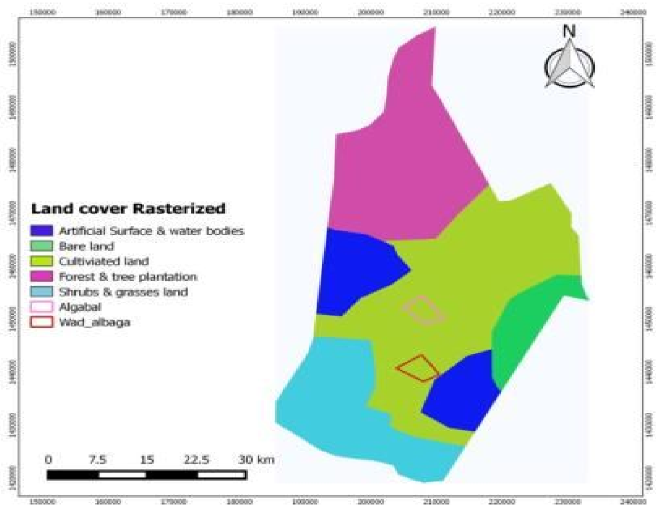

Figure 5:Land cover map of the study area

Slope map: The slope of the catchment affects how quickly water will runoff during a rain event. This was also clipped from the region slope derived from 30 meters pixel size Aster-DEM. Filtering to resolve for undefined areas was performed using majority filter. This layer was reclassified into five classes as indicated in (Table 6).

In situ RWH is not recommended for areas where slopes are greater than 5% due to uneven distribution of runoff and large quantities of earthwork required which is often costly (Ketsela, 2009). The two locations were in slope less than 2% which indicates the best site for *in situ* RWH (Figure). The outcomes of this study are similar to those of Mahmoud and Alazba (2014)who found that a steep area will shed runoff quickly, while, a less-steep, flatter area will cause the water to move more slowly, raising the potential for water to remain on the soil surface. Thus *in situ* structure is generally more appropriate in areas having a rather flatter slope.

Table 6: Suitability rank for slope of the region (from Mahmoud *et al*., 2015)

No	Slope (%)	Description	Ranking Classes
1	0-0.4	Flat	5
2	0.5-1	Slightly flat	4
3	2-7	Moderately sloping	3
4	8-15	Strongly sloping	2
5	16-32	Mountainous	1

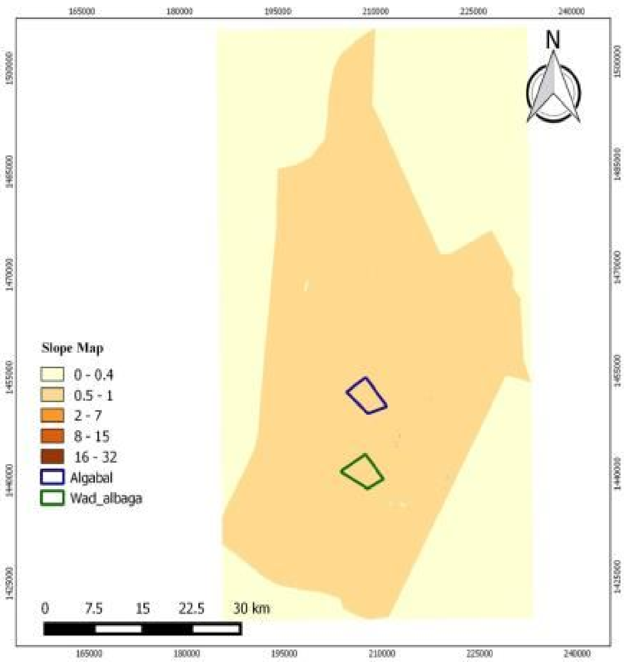

Figure 6: Slope map of the study area

AHP model outputs*:* The result from the pair-wise comparison areas are presented in the below matrix table. During pair-wise comparison, criteria were rated based on the case studies of Ketsela (2009) and of Mahmoud and Alazba (2014) in Ethiopia and Saudi Arabia, respectively. The relative weights for each criterion and suitability rank for classes were assigned for *in situ* RWH according to many literature reviews (Table). Consequently, the texture criterion is 7 times as important as land cover. Meaning that, the land cover criterion is 1/7 as important as soil texture criterion (Table 7).

The Consistency Ratio (CR) of the matrix, which shows the degree of consistency that has been achieved during comparing the criteria or the probability that the matrix ratings were randomly generated, was 0.026 which is acceptable as the values are less than or equal to 0.1 (Saaty, 1977). CR is calculated by dividing the consistency index (CI) by the random inconsistency (RI) (Saaty, 1977).

$$CR = CI / RI$$

Where:
CI = 0.029 (is calculated by the model)
RI = 1.12 (is constant given by (Saaty, 1977)
CR =0.029/1.12 = 0.026 which is less than 0.1 and indicate that the judgments are trustworthy and reasonable.

Table 7: pair-wise comparison matrix for in-situ structures

	Texture	**Runoff Depth**	**Rainfall surplus**	**Land Cover**	**Slope**
Texture	1	2	3	7	4
Runoff Depth	1/2	1	4	5	3
Rainfall surplus	1/3	1/4	1	4	3
Land Cover	1/7	1/5	1/4	1	½
Slope	1/4	1/3	1/3	2	1

As result, one location (Wad Albaga) fellwithin the good portion with 46.04% while Algabal lied in the moderately good area with a percentage of 18.6% out of the total area (Table 8).

Table 8: Suitable areas of the study area obtained from the collected soil data

Suitability levels	**Area (km^2)**	**Percentage (%)**
Excellent	198.2	10.81
Good	844	46.04
Moderate	341	18.60
Poor	328.1	17.95
Unsuitable	121	6.60
Total	1833.2	100.00

As result, one location (Wad Albaga) fellwithin the good portion with 46.04% while Algabal lied in the moderately good area with a percentage of 18.6% out of the total area (Table 8).

Table This indicates that the good portion has the large space in which *in situ* water harvesting structures can be applied. This also can be attributed to the fact the soil texture of this part is sandy clay loam which was classified as the best soil for *in situ* water harvesting structures. These results are similar to those of Ketsela, (2009) who demonstrated that the loamy soils are most suitable for *in situ* RWH whereas clay soils are less suitable because of their low infiltration capacity and risk of water logging.

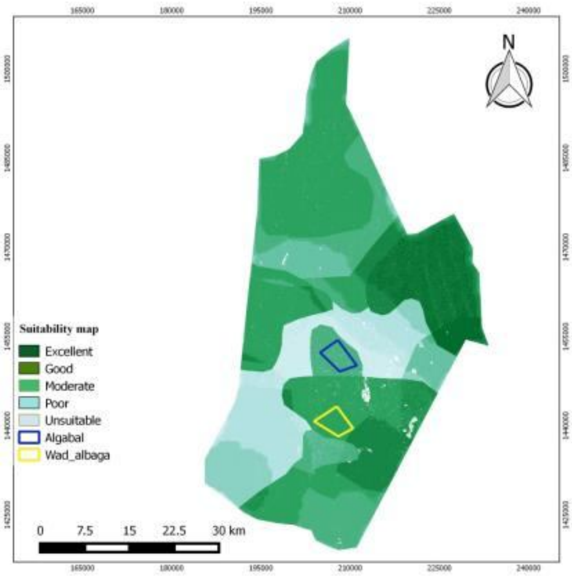

Figure 7: Suitability map of the study area using the collected soil data

Table revealed that terrace bunds (Algabal location) were located at the moderate portion whereas semi-circular bunds (Wad Albaga location)were located at the good portion. However, in both cases, Wad Albaga location was found to be the best site compared to Algabal location which is classified as moderate site. These differences can be attributed to the soil texture classes of both sites where Wad Albaga has the highest ranking (Sandy clay loam) followed by Algabal location which was ranked as the fourth in terms of preferences (Sandy clay). The findings of this study were similar to those of Mahmoud and Alazba (2014) who stated that soil texture being responsible for seepage, was more important than the other criteria which in turn result in a higher weight for soil texture.

Table 9: Suitablity classes of the two locations

Locations	**Soil data map**
Algabal	Moderate
Wad Albaga	Good

CONCLUSION AND RECOMMENDATIONS

Identification of potential sites for *In situ* water harvesting is an important step toward maximizing water availability and land productivity in arid and semi-arid regions. Therefore, *in situ* water harvesting can be used to provide water for agricultural use in arid regions where there is no surface water available for human activities.

The generated suitability map revealed that Wad Albaga location (semi-circular bunds) fallen within the good portion with whereas, Algabal location (bund terraces) lies within the Moderate area. This can be attributed to the well-constructed layers and the best site selection which is found to be appropriate to rainwater harvesting.

GIS proved to be a flexible, time saving and cost-effective tool to screen large areas for their suitability of both in-situ RWH structures. The suitability maps provide an easy to understand source of information to quickly identify areas that are more promising than other areas for RWH structures.

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تحليل المواقع الملائمة لتقانات حصاد المياه المكانية بإستحدام نظم المعلومات الجغرافية والإستشعار عن بعد بمحلية شيكان

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مستخلص البحث: أجريت الدراسة في محلية شيكان في عام 2017 لتحديد المواقع المناسبة لحصاد مياه الامطار (Rainwater Harvesting).إختيار المواقع المناسبة لتقنيات حصاد المياه يمكن أن يساهم إنجاح إنتاج المحاصيل بشكل أفضل في مثل هذه المناطق.تقنيات حصاد المياه الحقلية (In-field) من أنجح الطرق التى تم إستخدامها لغرض التكيف مع التغير المناخى فى محافظة شيكان لتحسين إنتاجية المحاصيل. الهدف الرئيسي من هذه الدراسة هو تحديد المواقع الملائمة لتقنيات حصاد المياه لمواجهة التغير المناخى من خلال استخدام تقنيات نظم المعلومات الجغرافية والاستشعار عن بعد في منطقتي جبل كردفان ومنطقة ود البقا في محافظة شيكان. وقد تم تطوير نموذج قائم على نظم المعلومات الجغرافية لإنشاء خرائط ملائمة لتقنيات حصاد المياه المكانية باستخدام تقييم متعدد المعايير. تم تحديد خمسة معايير ملائمة (نسيج التربة ، عمق الجريان السطحي ،فائض هطول الأمطار،الغطاء الأرضي، والإنحدار) لتقنيات حصاد المياه المكانية، وتم اختيار خمسة مستويات ملائمة لكل معيار (ممتازة ، جيدة ، متوسطة ، سيئة ، وغير مناسبة).تم تخصيص الأوزان للمعايير بناءً على أهميتها النسبية لتقنيات حصاد المياه المكانية باستخدام عملية التسلسل الهرمي التحليلي (Analytical Hierarchy Process). باستخدام برنامج QGIS و ArcGIS ، حيث تم إعداد جميع خرائط المعايير الخمسة ومن ثم خريطة ملاءمة منطقة الدراسة. أظهرت النتائج على أن، تقانات الأشكال نصف الدائرية فى منطقة جبل ود البقا وقعت في جزء جيد من الخريطة (844 km2) والذي يمثل ,46.04% ، في حين أن موقع جبل كردفان (التروس) يقع في الفئة المعتدلة (341 km2) مع 18.6%. لذلك ، يُعتبر موقع الجبل موقعًا معتدلا و يعزى السبب إلى قوام التربة الذي كانت تربتة طينية رملية وتم تصنيفه في المرتبة الثانية من حيث الأهمية مقارنة بمكان ودالبقاوهى الطين الطمي الرملي. تعمل خريطة الملاءمة التي تم إنتاجها على تسهيل تحديد المواقع التي يمكن أن يستخدم فيها هياكل حصاد المياه المكانية المختلفة. وخلصت الدراسة إلى أن تحديد المواقع المناسبة باستخدام نظم المعلومات الجغرافية هو وسيلة فعالة من حيث التكلفة وتوفير الوقت لاكتشاف المواقع الأكثر ملاءمة لهذه التقانات.

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