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Mapping Potential Sites for Rainwater Harvesting (Dams) in the Pan-Handle of Jordan Using Geographic Information Systems

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Abstract: The largest environmental problem that Jordan faces is the water shortage and scarcity. Responding to this chronic challenge, the Jordan Government has adopted a multi-faceted approach to meet the growing demand on water. One of the suggested methods is rainfall harvesting projects. The fundamental goal of this study is to assess the most suitable sites for such projects in the Pan-Handle of Jordan by employing geographic information system (GIS). Thematic maps of rainfall, slope, land use, soil texture, distance to roads, distance to faults, distance to settlements, distance to wadi, flow accumulation and curvature were prepared and used in assessing site suitability for rainwater harvesting using a GIS interface. The multi-criteria evaluation technique was applied which is primarily concerned with how to combine the information from several criteria to form a single index of evaluation. In this technique, weight was assigned to the data layers to reflect their relative importance and ratings were given to reflect importance of spatial variation within the layer. The analytical hierarchy principle (AHP) was used to assign weights for the parameters used in the model. The rainwater harvesting model (RHM) was developed for dams, showing spatial rainwater harvesting index (RHI) in the study area. The RHI in the study area ranges between 0 and 1690. This range was reclassified and assigned scores that ranged from 1 to 5 based on site suitability for rainwater harvesting by dams. Here, 1 represents very low potential for harvesting rainfall harvesting and 5 represents very high potential. The percentage of the area covered by the highly suitable and very highly suitable classes is 0.07% (13 km^2) and 0.017 (3 km^2), respectively.

Key words: Missing

INTRODUCTION

In arid regions, the potential sources of good-quality water are limited because of the insufficient amounts of rainfall and the very high potential evaporation, exceeding the potential rainfall by several times [1]. The scarcity of water and the high cost of its development have long been recognized in arid regions such as Jordan, where surface water and groundwater resources are limited. Arid and semi-arid regions are characterized by low erratic rainfall, periodic droughts and different associations of vegetative cover and soils [2]. In arid areas, rainfed agriculture is usually not possible, whereas in the semi-arid areas agriculture harvest is likely to be irregular, although grazing is satisfactory [2]. Jordan has one of the lowest levels of water resource availability, per capita, in the world. Water scarcity will become an even greater problem over the next two decades as the population doubles and climate change potentially makes precipitation more uncertain and variable. Management of water resources is therefore a key issue facing national government authorities. Increasing overall water extraction to meet demand carries a high cost; Jordan is now accessing non-renewable water resources from fossil deep-water aquifers. Water quantity and quality also have major health and environmental impacts. Responding to the challenges of water scarcity, the Jordanian government has adopted a multi-faceted approach designed to both reduce demand as well as increase supply by utilizing new water resources. With a considerable portion of the population living in the arid to semi-arid conditions of the country, it is necessary to look for different ways of increasing water resources such as water harvesting. Water harvesting is defined as a method

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of water collection; it is applied in arid and semi-arid regions, where rainfall is either not sufficient to sustain a good crop and pasture growth or where, due to the erratic nature of precipitation, the risk of crop failure is very high [3]. Water harvesting is an ancient art practiced in the past in many parts of the world [4], that has predominantly been used in dry areas to collect and supplement scarce water resources [5]. Rainwater harvesting has recently been promoted to solve water problem for agricultural and domestic uses in semi-arid regions of China [6]. The need for water harvesting arise from many factors such as low rainfall and uneven distribution, high losses due to evaporation and runoff and an increased demand on water due to population growth [7]. Harvesting and conservation of rainwater is central to the attainment of economic as well as the financial sustainability of water deficit areas [8]. It is known to increase cropping intensity and increase groundwater levels [9]. Water harvesting can be accomplished through in situ harvesting, soil conservation methods and increasing infiltration for recharge of groundwater [10]. The sitting of water collection structures depends on a multitude of factors, ranging from basic hydrologic characteristics of the local area [11,7] to the socioeconomic interests of the government or local authorities. Geographic information system (GIS) has been recommended as a decision-making and problem solving tool in rainwater harvesting during the decision-making process [12]. In this research, a Web-based GIS-hydrologic modeling system was designed to implement the approach adopted for selecting the most suitable and practical location for building water harvesting reservoirs. GIS can handle complex network problems, such as stream network analysis. There are, of course, other types of network analysis, involving road networks. GIS could be used to model the flow of water through a river system, to plan a flood warning system and to model water harvesting potential. The main objectives of the study include: (1) Evaluating rainwater harvesting potential by dams in the Hamad Basin and (2) Developing a GIS model for rainwater harvesting in the study area.

Study Area: Hamad Basin is a flat plateau covering a very large area (18,250 km^2) which includes the southern part of Syria, the western most part of Iraq, a part of northwest Saudi Arabia and the pan-handle of Jordan (Fig. 1). Elevation in the basin is in the of range 600-1000 m above the sea level; its maximum height is found in Rutbah uplift at Jabal Aneizeh, the meeting point of Jordan, Iraq and Saudi border. The study area is located 694894.083269-716550.618625 N and 531577.727778-515310.989700 E (JTM).The climate of Hamad basin is arid, characterized by hot dry summers and cold and relatively wet winters. Rainfalls occur between October and May in the form of short, intense storms of variable intensity and spatial distribution. The mean annual rainfall in the basin ranges from 30 mm to 110 mm. The weighted average rainfall is 74.4 mm. The average volume of annual rainfall in Hamad basin is about 1,376 MCM.

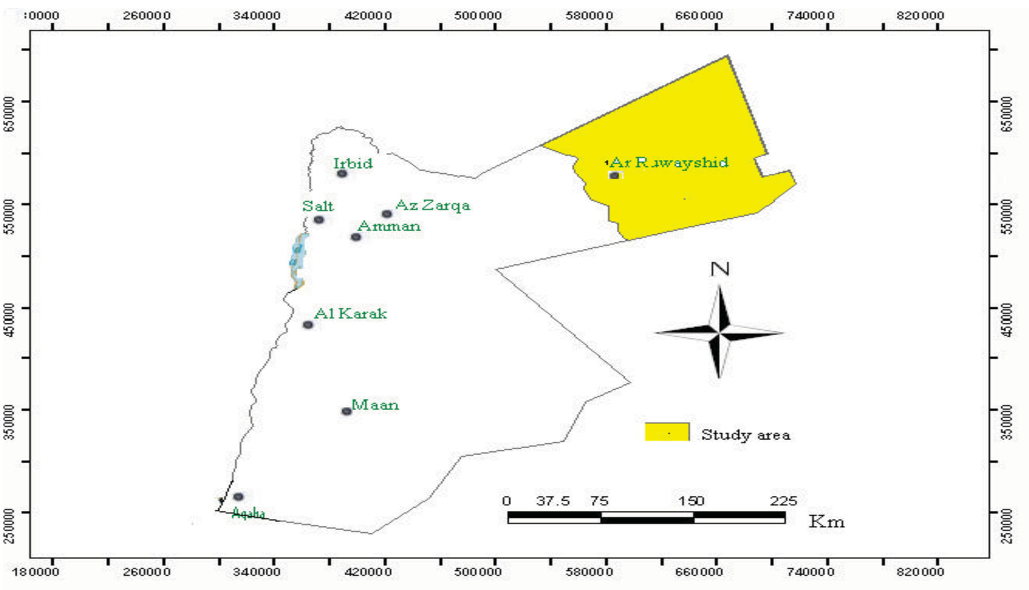

Fig. 1: Location map of the study area

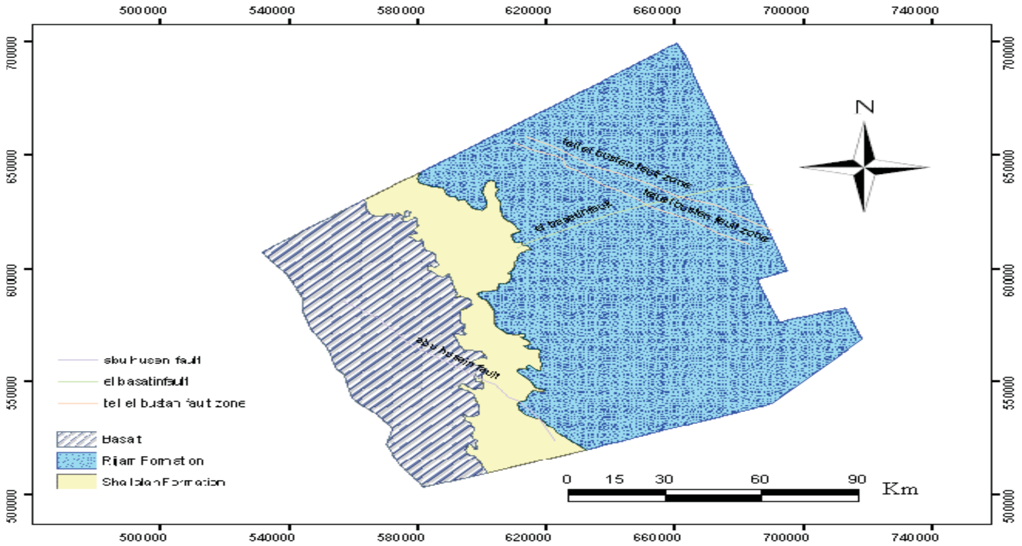

Fig. 2. The outcropping geological formations in the study area

The outcropping formations in Hamad basin (Fig. 2) are Shallaleh and Rijam in the central and eastern parts, both are tertiary in age. The west Hamad is dominated by Miocene to Pleistocene basalts. The Rijam chert-limestone formation of Paleocene age consists of chalky limestone, chalk, chert and microcrystalline limestone with beds and nodules of black chert. The Shallala formation of Eocene age crops out in central Hamad, where it is composed of chalk, chalky marl with thin beds of marly limestone, which are locally bituminous, containing glauconite and phosphate.The basalt group is Miocene to Pliocene in age. They crop out in west Hamad and continue westwards and northwards into Azraq and Syria and southwards into Saudi Arabia. They consist of flood lava, dykes, pyroclastic and volcanic cones. The aquifer system in the study area consists of three aquifer complexes: the upper, middle and lower aquifer complexes. The lower aquifer complex is formed from sandstone and it is found as one unit in the south and two units in the north separated by thick limestone and marl layers. The lower aquifer complex is confined by low permeability marls and consists of poorly consolidated, early Cretaceous sandstones [13]. The middle complex (the upper and middle Cretaceous complex) consists of limestone, dolomite, marl stone and chert beds. The middle aquifer complex is confined, being separated from the upper aquifer complex by low permeability marls and chalks. This aquifer complex crops out in the west and southwest of the Azraq basin, where it is recharged. The middle aquifer complex consists of the Amman formation (an aquifer), the Ruseifa formation (an aquitard) and the Wadi Sir Formation (an aquifer).

Groundwater in the Amman aquifer lies between 420 m and 590 m below the surface [13]. The upper aquifer complex, which is the mostly exploited, consists of two main systems: the basalt aquifer system and the sedimentary rocks and alluvial deposits of Tertiary and Quaternary age [14]. The upper aquifer complex is unconfined, consists of Quaternary alluvial deposits, Miocene-Quaternary basalt flows, the Eocene Shallala formation and the Paleocene Rijam formation. Water in the alluvial deposits is within a few meters of the land surface and can be reached with hand-dug wells [13].

MATERIAL AND METHODS

Research Method: Water harvesting planning usually consists of the following steps: 1) collecting needed data on hydrology, soil characteristics, land cover and topography of the investigated area, 2) utilizing computer based analytical environment for data capturing, storage, manipulation and analysis, 3) performing comprehensive hydrologic analysis of the investigated area based on collected hydrologic data and hydrologic modeling and 4) using decision making tools for evaluating the different alternatives of water harvesting systems, including site selection and storage volume.

A GIS application is used to model the best sites for rainwater harvesting in the Hamad basin, NE Jordan. A multi-criteria evaluation (MCE) technique is adopted in this study. MCE techniques are primarily concerned with how to combine the information from several criteria to form a single index of evaluation [15]. In this technique, 'weight' is assigned to the data layers to reflect their

Table 1: Parameters of water harvesting model with their weights and ratings

Criterion	Weight	Category	Rating
Annual rainfall (mm\year)	24.98	>100	10
		50-100	5
		<50	0
Flow accumulation	24.98	0-10,000	1
		10,000-40,000	2
		40,000-76,000	3
		76,000-106,000	4
		106,000-137,000	5
		137,000-177,000	6
		177,000-268,000	7
		268,000-598,000	8
		598,000-837,000	9
		837,000-1,294,175	10
Slope (%)	5.29	0-3	4
		3-5	3
		5-10	2
		>10	1
Distance to wadi (meter)	16.96	0-50	4
		>50	0
Land use	11.52	Urban area	1
		Orchard area	2
		Cultivated area	3
		Range land	4
Soil Texture (Clay content %)	7.80	>35	4
		18-35	3
		<18%	2
Distance to settlement (meter)	2.44	250-500	4
		500-1000	3
		1000-2000	2
		>2000	1
		0-250	0
Distance to roads (meter)	2.44	250-500	4
		500-1000	3
		1000-2000	2
		>2000	1
		0-250	0
Distance to faults (meter)	3.59	>500	1
		0-500	0
Curvature	1	-0.5-0	1
		0-0.5	0

relative importance. Rainwater harvesting in a geologically complex terrain requires consideration of a number of factors-both natural and anthropogenic. It is important to understand the control of these factors on the water harvesting project of any area for optimal exploitation. As such, to arrive at a clear picture of the situation, the controlling factors have to be treated and integrated giving weight that is specific to a particular area. In this backdrop, the present study is aimed at testing the efficacy of MCE technique used in GIS environment as framework for decision making problems pertaining to water harvesting project. The parameters that were used to model the potential sites of water harvesting are shown in Table 1; these include: annual rainfall (mm/year), flow accumulation, slope (%), distance to wadi (m), land use, soil texture (clay content %), distance to settlement (m), distance to roads (m), distance to faults (m) and curvature.

Table 2: Data type and source used in the present study

Original data	Derived maps	Source
DEM	Slope	Radar data
	Curvature	
	Flow accumulation	
Satellite Image and Topographic maps	Stream (wadi)	http://www.landsat.org
	Settlemantal	Topographic sheets from the Royal Jordanian Geographic Center (scale 1:50000)
	Roads	
	Land use	
Geologic map	Faults	Natural Resources Authority
Rainfall data	Rainfall distribution map	Meteorological Department
Soil	Soil texture	Ministry of Agriculture

Essential information on the standards applicable international and national for identifying the best places for the establishment of water harvesting were applied to implement the model. Some general guidelines have been taken into account when selecting the sites of water harvesting projects; they are applied in the Directorate of Water Harvesting in the Ministry of Water and Irrigation. To assign ratings of the parameters the guidelines of the Ministry of Agriculture were followed.

There Are Two Methods for Assigning Weights of Parameters

Simple Additive Weighting (SAW): It is probably the best known and very widely used method of multiple attribute decision making. A score in the SAW method is obtained by adding contributions from attribute. Since two items with different measurement units cannot be added, a common numerical scaling system such as normalization is required to permit addition among attribute values. The total score for each attribute can obtained by multiplying the scale rating for each attribute value by the importance weight assigned to the attribute and then summing these products over all attribute [16].

Analytical Hierarchy Principle (AHP): Using the analytical hierarchy principle (AHP) nine point scale, a paired comparison matrix [17], was prepared for the ten parameters selected for Hamad basin. Individual class ratings and map scores were then worked out.

Data Source and Preparation: To assess the potential sites for rainwater harvesting in the Hamad basin several factors are considered: annual rainfall, slope, flow accumulation, distance to wadi, land use, soil, urban area, roads, faults and curvature. Table 2 shows the data type and sources used in the present study.

Geoprocessing and Model Building: After preparation of all essential maps of the parameters in the model, different themes were classified according to the criteria set by the used model (Table 1). Classification is the process of sorting or arranging entities into groups or categories on a map. Different classes are identified for each parameter then suitable rating was given to each one. By now all themes were in the final format to be used in the formula of the water harvesting index (RHI) to produce a water harvesting potential map. The water harvesting index value was calculated by using the following equation:

$$\text{Rainwater harvesting Index (RHI)} = (((R_w * R_r)+(FA_W * FA_R)+(S_w * S_r)+(LU_w * LU_r)+(ST_w * ST_r)+(DR_w * Dr_r)+(DW_w * DW_r)+(DU_w * DU_r)) *(F_w * F_r)) *(C_W * C_R).$$

Where:

R: rainfall, FA: flow acumalation, S: slope, LU: land use, ST: soil texture, DR: distance to roads, DW: distance to wadi, DU: distance to urban, F: faults, C: curvature, w: weight, r: rating.

RESULTS AND DISCUSSION

This section illustrates the results of all parameters used in modeling water harvesting potential in the Hamad basin.

Faults: To minimize the impact of faults on water harvesting a buffer zone of 500 m was constructed (Fig. 3). The faults map was categorized into two classes and assigned suitable ratings according to criteria set in Table 1.

Drainage System and Distance to Wadi: Drainage system is an important factor in defining the best sites for water harvesting. Drainage system of the study area can be described as dentritic.

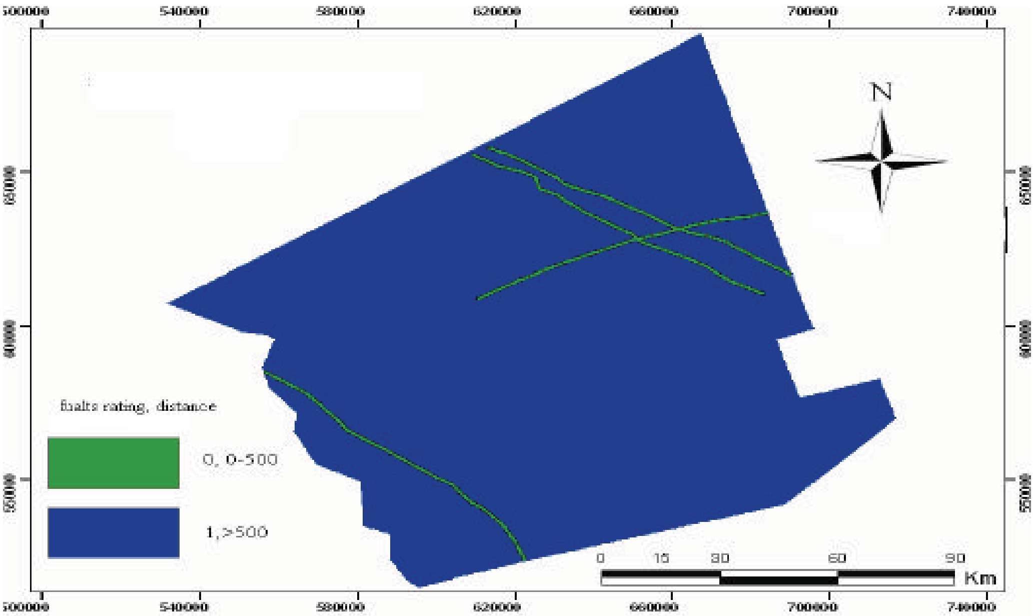

Fig. 3: Spatial distribution of faults buffer zone rating

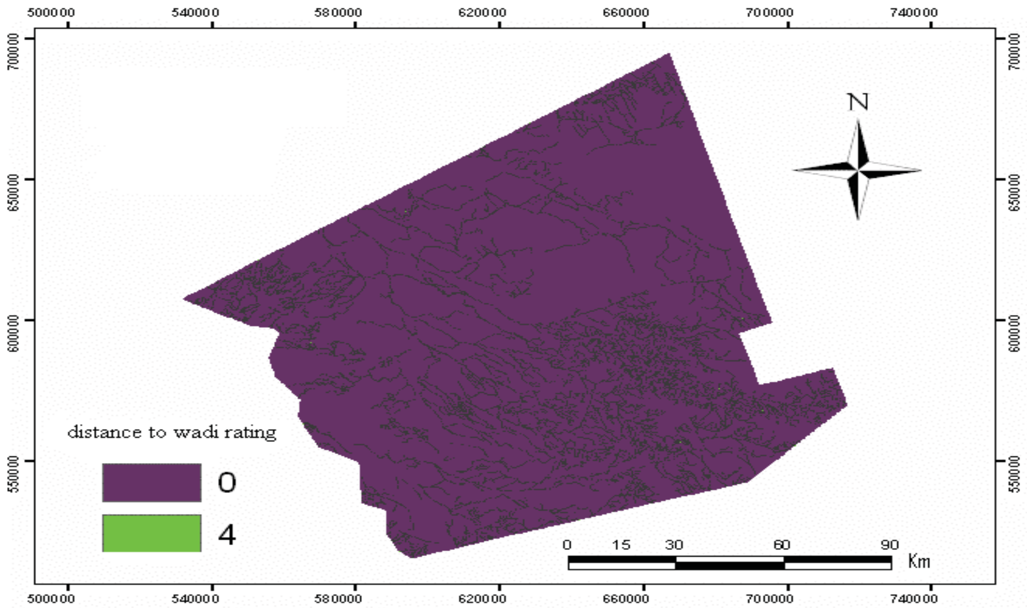

Fig. 4: Distance to wadi rating

Stream network was derived from the ETM+ Landsat imagery. For dams it is recommended to be within 50 m distance from streams. Because dam must be as close as possible of the wadi, therefore, a buffer zone was created around the stream network and assigned a rating value equal to 4 (Fig. 4). Areas beyond the buffer zone assigned zero value.

Slope: A digital elevation model with 90 m cell size resolution was used to derive slope map (Fig. 5a). Slope in the study area ranges between 0 % and 32.9 %. Slope values were grouped into four classes and given suitable rating in the range 0-4 as shown in (Fig. 5b). The dominant rating class is 4 which occupy about 91 % of the basin area.

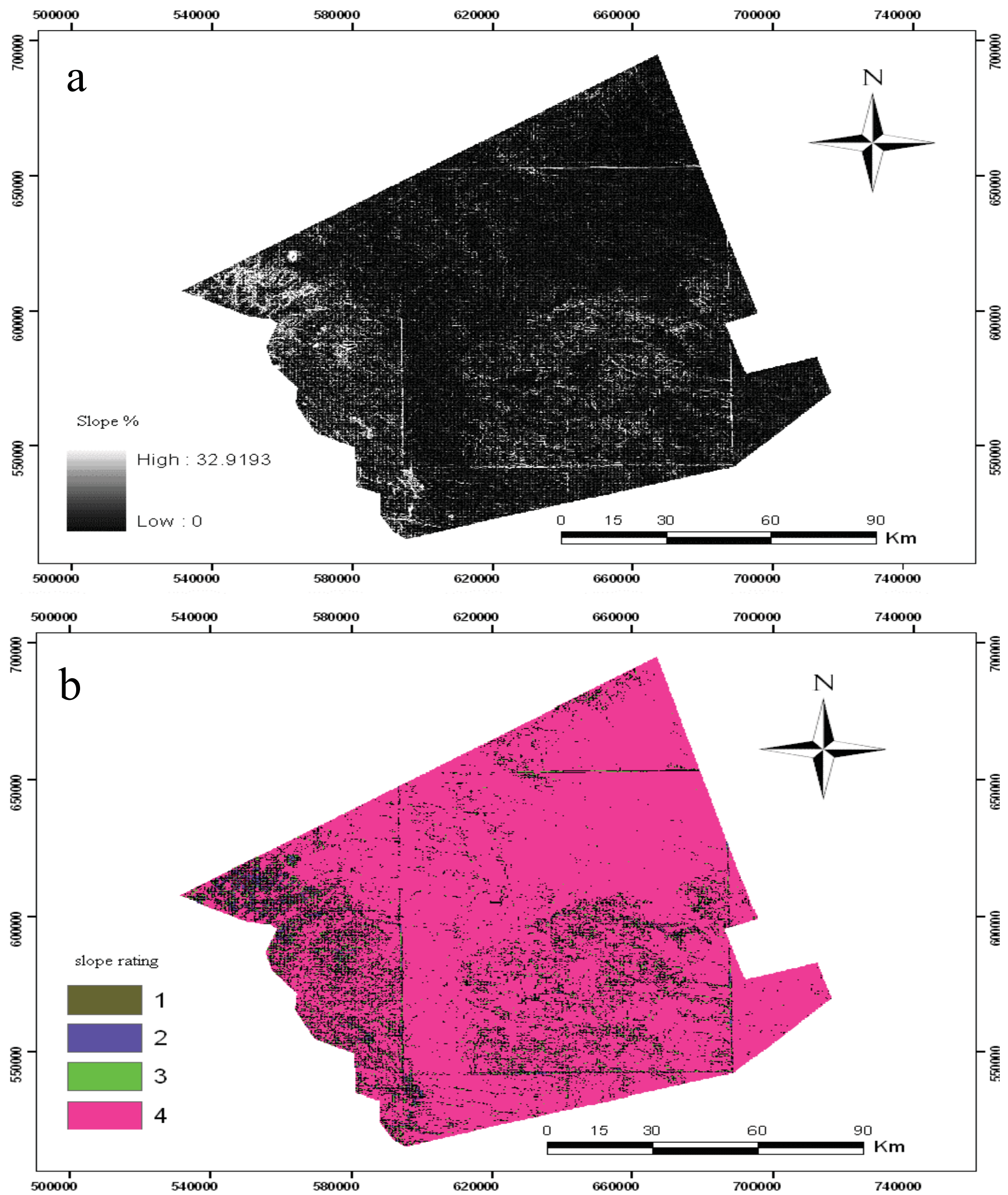

Fig. 5: a) Spatial distribution of the slope (%) in the study area; b) Rating values of the slope

Flow Accumulation: The flow accumulation of a terrain is an index which estimates the surface runoff for each cell in the terrain; the flow accumulation of a cell is defined as the total area of the grid cells which flow through that cell per unit width of contour [18]

The flow accumulation map of the study area was derived from the digital elevation model. The maximum flow accumulation in the study area is 129,418 (Fig. 6a). Flow accumulation values were grouped into ten classes and given suitable rating in the range 1-10 as shown in (Fig. 6b). The dominant rating is one.

Soil Data: To apply water harvesting model we need to determine the soil texture (clay content) in the Hamad basin. Clay content in the study area ranges between 6 % and 58.5 %, which were grouped into three classes and given suitable rating (Fig. 7). The lowest rating is two and highest is four.

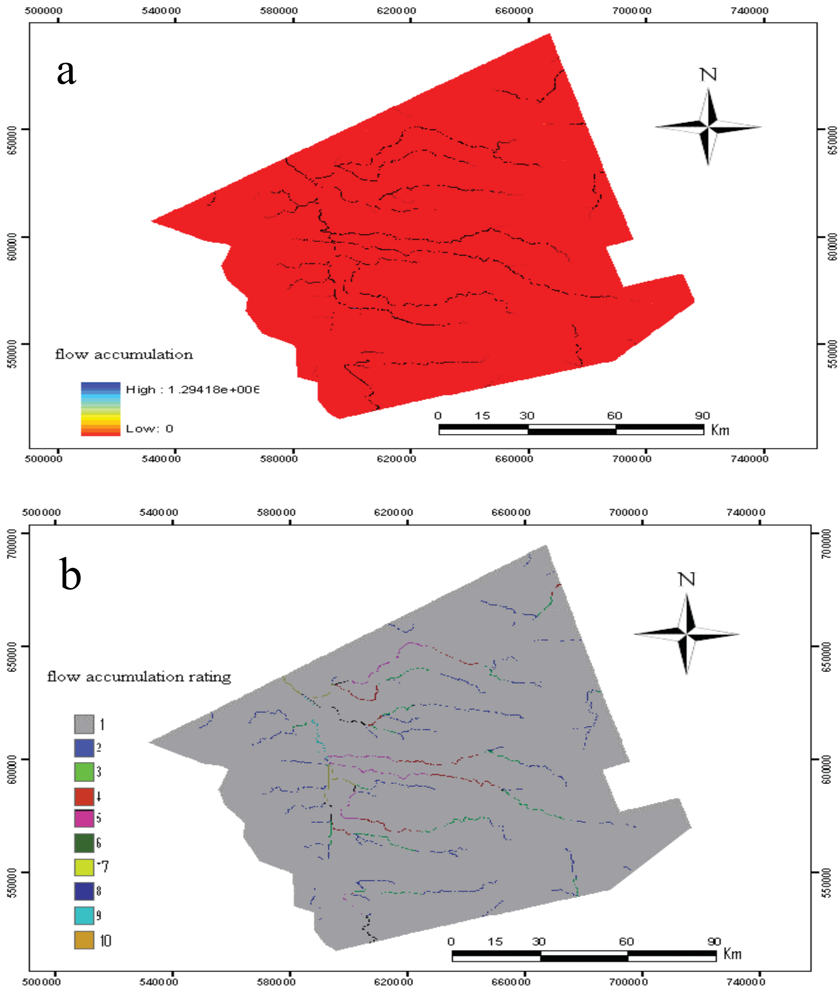

Fig. 6: a) Spatial distribution of the flow accumulation; b) rating values of the flow accumulation

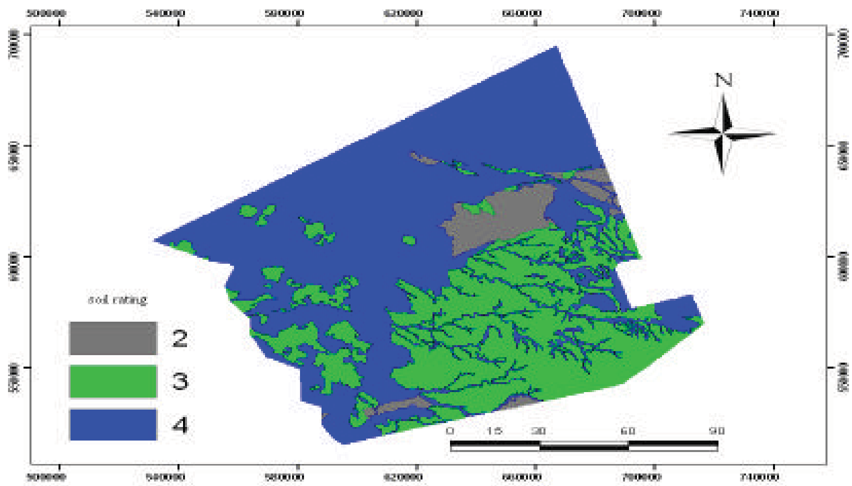

Fig. 7: Spatial distribution of the rating values of soil clay content

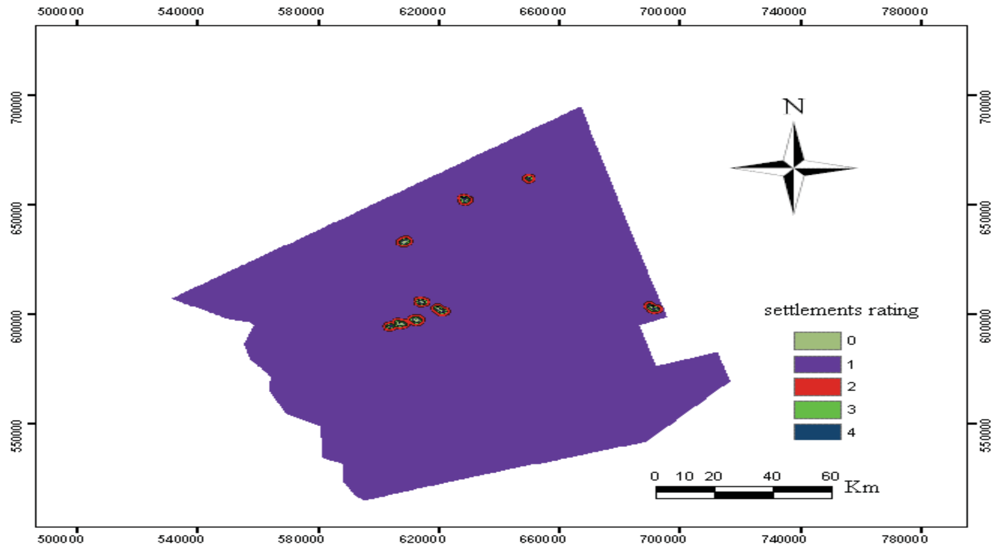

Fig. 8: Settlement area rating values

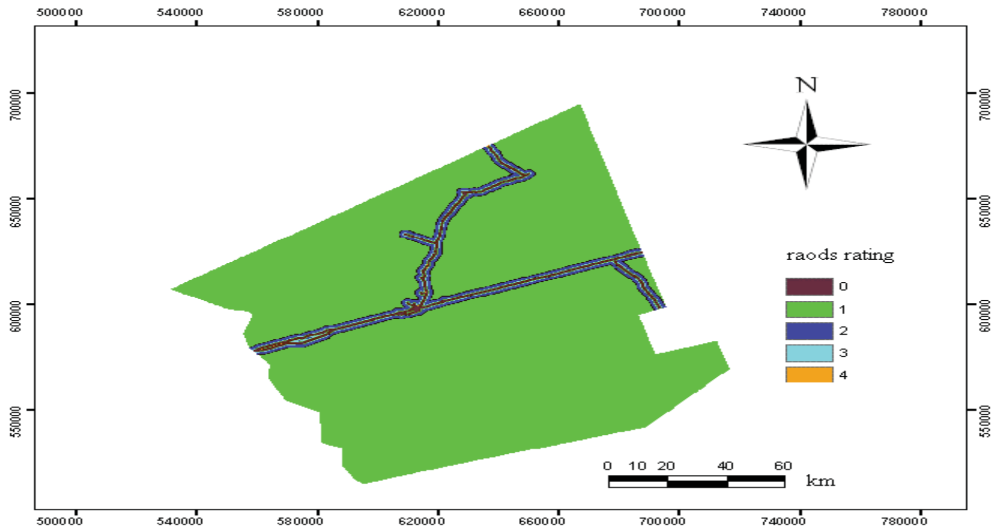

Fig. 9: Distance to road rating values

Distance to Settlements: The best distance from settlements areas ranges from of 250 m to500 m, where it is the best in the water harvesting projects. Multiple buffer zones were created around settlements and assigned rating values as set in criteria of water harvesting model. The basin is dominated by class value 1 (Fig. 8) with an area coverage of about 98.8 %.

Distance to Roads: Roads map was derived from the topographic maps and satellite imagery. The importance of site location for water harvesting depends partially on the distance to roads. Therefore, the distance from roads (Fig. 9) is classified into 5 zones and assigned rating values accordingly. The dams must be at least 250 m away from roads (rating value=0). The distance 250-500 m is the best zone for water harvesting, then the values decrease afterwards.

Land Use: Land use is the way in which land is used. Land use map was derived from the topographic maps and satellite images. There are 4 classes of land use in the study area: range land coverage about 99.5 %, cultivated area coverage about 0.41 %, urban area coverage about 0.03 % and orchard area coverage about 0.017 %.

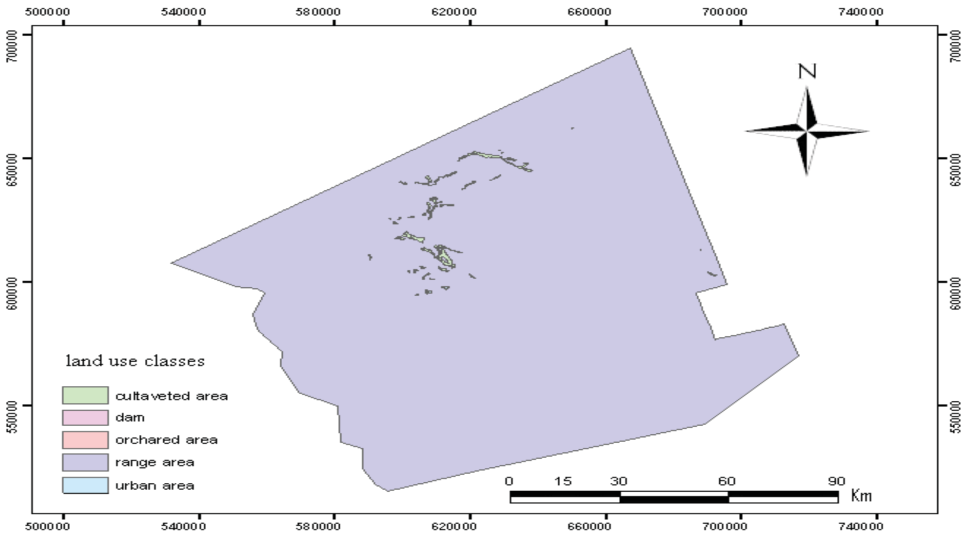

Fig. 10: Map of Land use/land cover in the study area

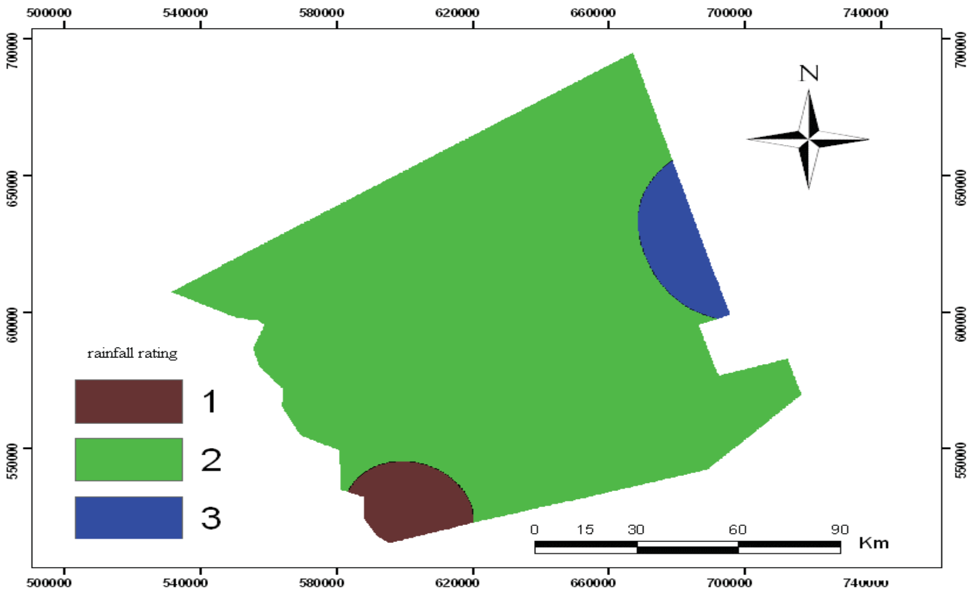

Fig. 11: Spatial distribution of rainfall rating values

Each land use class was assigned a rating value representing its importance in water harvesting. The dominant rating class is 4 which represented range land (Fig. 10).

Rainfall Map: By using the average annual rainfall recorded at the rain gauges, a rainfall map of the study area was derived by interpolation in ArcGIS. The mean annual rainfall is in the range of 30-120 mm. The lowest average rainfall is found in the southwest of the basin and gradually increases toward the northeast. Average annual rainfall was grouped into three classes and given ratings (0-10) accordingly (Fig. 11). Most of the basin area is dominated by the class 50-100mm.

Curvature: Curvature is the second derivative of the surface or the slope of the slope [18]. Two optional output curvature types are possible; the profile curvature is in the direction of the maximum slope and the plan curvature is perpendicular to the direction of the maximum slope. The purpose of defining curvature is to help determine the best sites for water harvesting projects.

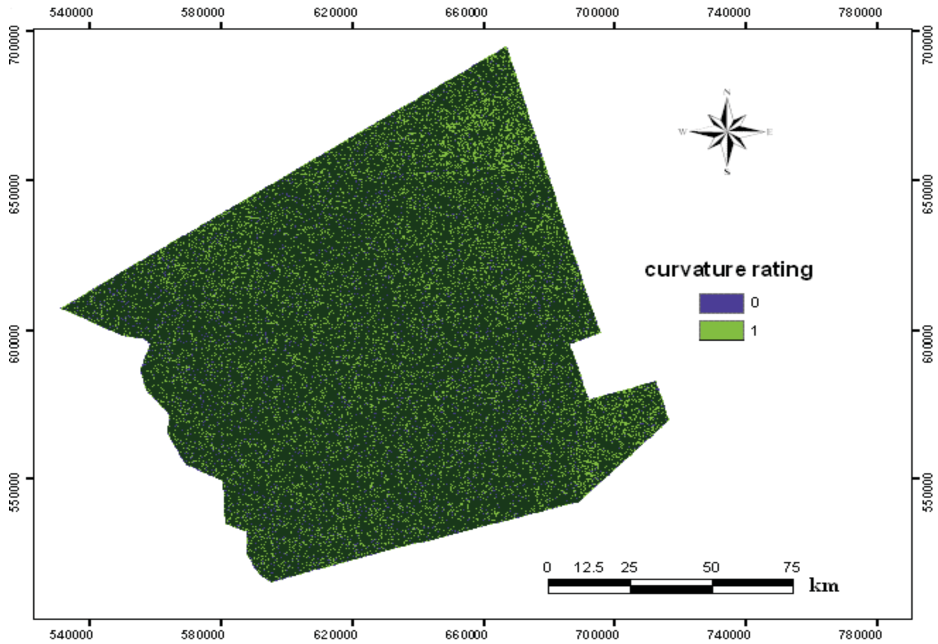

Fig. 12: Rating values of curvature in the Hamad basin

The curvature map was derived from the digital elevation model. It was classified in two classes and each class given the suitable rating (Fig. 12). Positive values of curvature is 0.5 (concave) with area coverage about 40.47 %, this area takes the rating 1. And the negative values is-0.5 (convex) with area coverage about 59.53 %, this area takes the rating 0.

Runoff Model: In hydrology a curve number (CN) is used to determine how much rainfall infiltrates into soil or an aquifer and how much rainfall becomes surface runoff. A high curve number means high runoff and low infiltration (urban areas); whereas a low curve number means low runoff and high infiltration (dry soil). The curve number is a function of land use and hydrologic soil group [18]. The values of CN used in this study are: 0 for Burqu dam, 55, 72, 81 and 86 for range land, 83 for Orchards area, 87 for Residential, 91 for Agriculture and 98 for paved areas. These curve numbers are assigned according to [18].

The average annual rainfall used to calculate the runoff (volume) is 75.4, which is determined from the rainfall map.

ArcCN-Runoff extension in the GIS was used to determine runoff model.

The average value of runoff is 72.46, with highest runoff (75.16 mm) due to the paved areas with 2405.12 km^2 area coverage. The lowest runoff value is 0, which represents Burqu dam.

The runoff volume is in the range of 0-42,621x10^5 m^3. This range was classified into three categories of equal intervals (Fig. 13): low, moderate and high. Most of the study area is occupied by the low class (79.6 %), followed by the high class (13.2 %) and moderate class (7.2 %).

Rainwater Harvesting Model: By integrating all the above discussed parameters, water harvesting index (RHI) was determined for dams. Using the overlay functionality in GIS, the RHI model was determined using AHP; its value was calculated for each unit area according to the following model:

$$RHI = [(R_w*R_r)+(FA_W*FA_R)+(S_w*S_r)+(LU_w*LU_r)+(ST_w*St_r)+(Dr_w*DR_r)+(DD_w*DD_r)+(DU_w*DU_r)]*(F_w*F_r)*(C_W*C_R).$$

Where:
R: rainfall, S: slope, LU: land use, ST: clay content, DR: distance to roads, DD: distance to wadi, DU: distance to urban, F: faults, C: curvature, F: flow accumulation, w: weight, r: rating.

Results of the model of water harvesting index using AHP method can be seen in (Fig 14a). The RHI ranged between 0 and 1690.6. This range was classified into five categories: very high suitable, highly suitable, moderate suitable, low suitable and very low suitable (Fig. 14b).

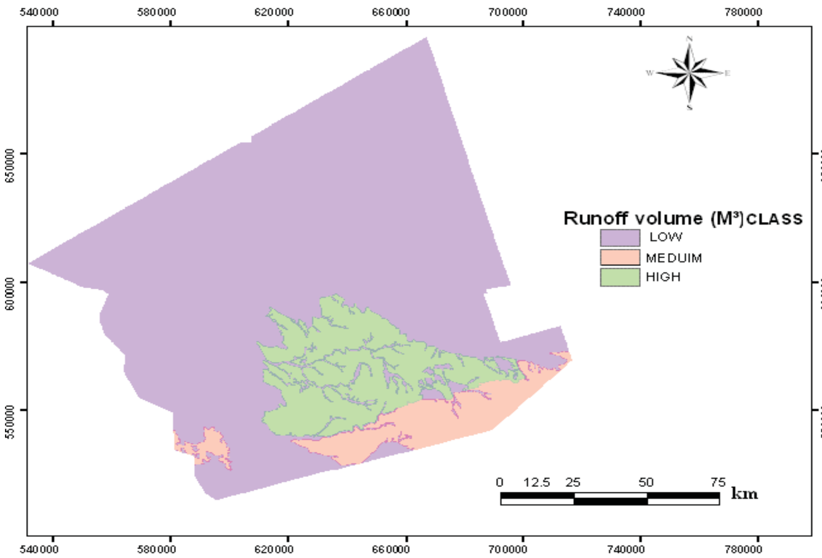

Fig. 13: Runoff volume classes in the Hamad basin

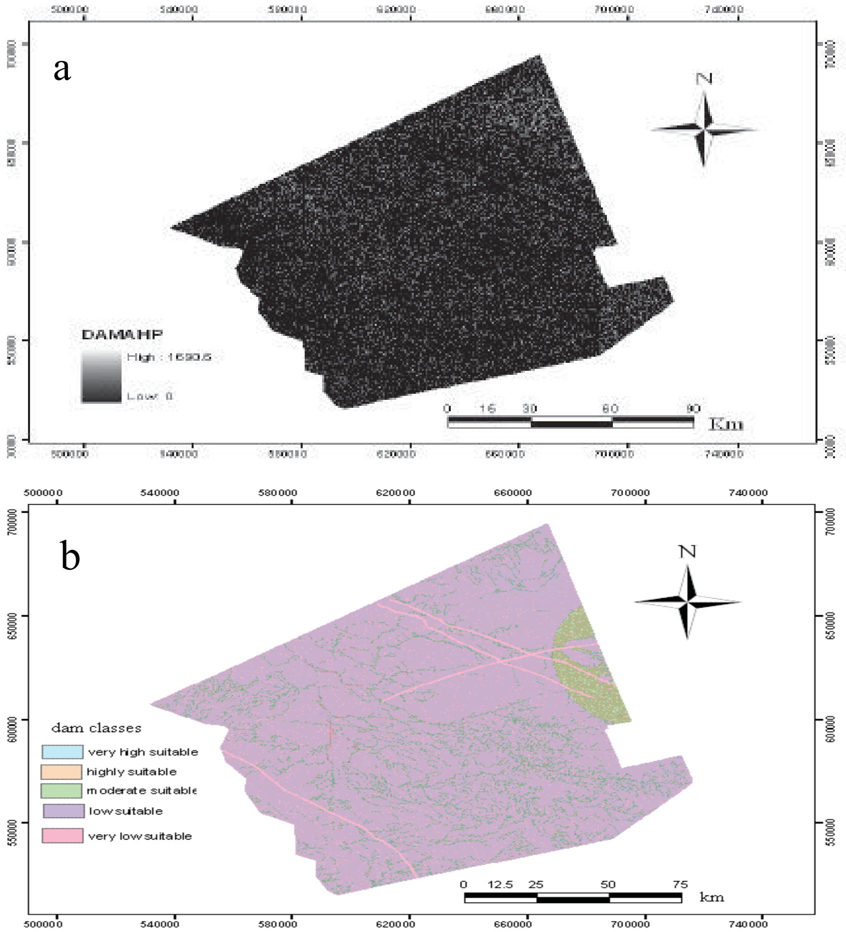

Fig. 14: a) Spatial distribution of the rainwater harvesting index; b) spatial distribution of the rainwater harvesting index classes

Fig. 15: Results of intersection of rainwater harvesting model and runoff

Table 3: Percentage of the area covered by each class of the water harvesting model

Class	% area
very high suitable	0.017
highly suitable	0.07
moderate suitable	0.05
low suitable	53.2
very low suitable	46.6

Most of the study area is occupied by the low suitable class 53.2 %, followed by the very low suitable class, moderate suitable class, highly suitable class and very high suitable class (Table 3).

To help determine the best sites for water harvesting projects in the Hamad basin, the RHI model classes were overlaid with the runoff volume model classes (Fig. 15). This figure shows the result of intersect between dam classes according to AHP and runoff volume classes. The results are classified into 12 classes. The study area is dominantly occupied by class 2; meaning low runoff and low suitable for water harvesting, the second dominant class in the study area is class 1, meaning low runoff and low suitable for water harvesting, followed by class 3, meaning, low to high runoff and low suitable; and class 6, meaning medium runoff and high suitable.

CONCLUSIONS

A rainwater harvesting model was built for the Hamad basin, NE Jordan by using a GIS interface. Results of the model run show that most of the study area is occupied by low suitable and very low suitable classes. Moderately-very highly suitable cover about 25 km^2 of the total study area (18,250 km^2).

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