

## Determining Potential Sites for Runoff Water Harvesting using Remote Sensing and Geographic Information Systems-Based Modeling in Sinai

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**Abstract: Problem statement:** Sinai is increasingly suffering from an overwhelming water crisis. Runoff Water Harvesting (RWH) could be a solution for this problem. The determined promising drainage basins for RWH could be used by the decision makers to propose appropriate controlling systems to overcome the problem of water scarcity and for implementing runoff farming and rain-fed agriculture. **Approach:** Remote sensing, geographic information systems, watershed modeling system were integrated to extract a multi-criteria-decision support system of nine thematic layers, namely; volume of annual flood, lineaments frequency density, drainage frequency density, maximum flow distance, basin area, basin slope, basin length, average overland flow distance and soil infiltration. These criteria were used for conducting a Weighted Spatial Probability Modeling (WSPM) to determine the potential areas for the RWH. The potential runoff available for harvesting was estimated by applying Finkel-SCS rainfall-runoff methods. **Results:** The WSPM classified Sinai into four classes that graded from high (3,201-6,695 km<sup>2</sup>), moderate (35,923-35,896 km<sup>2</sup>), low (13,185-16,652 km<sup>2</sup>), very low (1.38-5.57 km<sup>2</sup>) for RWH. Promising watersheds like those of Abu Taryfy, Hama El Hassana, Gerafi, Watir, Geraia, Heridien, Sidri, Feiran and Alaawag, are categorized as high-moderate RWH potential basins. **Conclusion:** These basins could be investigated in detail with larger scale to determine the appropriate locations for implementing the RWH structures and techniques. Implementing systems and techniques of RWH in the potential watersheds could open new opportunities for sustainable development in the area.

**Key words:** Watershed modeling, drainage systems, hydrographic parameters, water resources scarcity, runoff calculations, spatial modeling

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### INTRODUCTION

The water scarcity is a major socio-economic crisis in Sinai Peninsula of Egypt (Fig. 1). Lack of proper water resources planning led to the drastic dropdown in Sinai urbanization and population development. Drought management, as well as sustainable agricultural production in arid and semi-arid areas of Sinai deserts will depend heavily on meticulous planning in the exploration, exploitation and utilization of water resources for favoring the human requirements. The agrarian system in Wadi El-Arish delta and the coastal belt in northern Sinai is to a large extent, rainfall dependent, which in turn is

highly erratic in nature. This calls for an intervention of a framework where Remote Sensing (RS), Geographic Information Systems (GIS) and watershed modeling tools could be useful in determining potential areas for Rainwater Harvesting (RWH). Planning should be based on the drainage basins, where effective methodologies and systematic information on the resources base are opt to quantify, analyze and formulate targets of water resources development by RWH.

Since 1982, the Egyptian government has promoted Sinai's tourism industry, but repositioning the newly formed settlements and urban communities are hampered mainly by the water scarcity.

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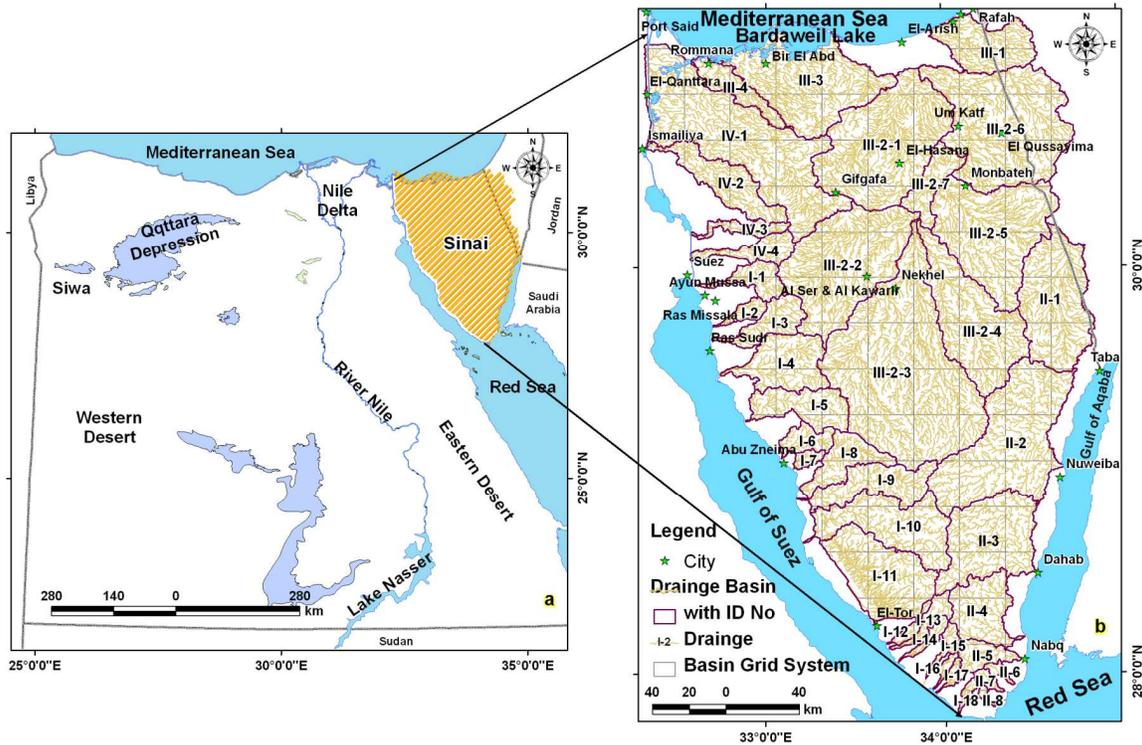


Fig. 1: a Location map, b drainage net map of study area (Extracted from Landsat ETM + image and GIS techniques)

Worth mentioning, no perennial surface water streams cross the peninsula and the flash floods, in spite of the fact that they are episodic and intermittent; no full utilization for them is performed. The groundwater resources in Sinai are relatively renewed by the sporadic rainfalls and flash floods occurring at its southern parts during the transitional periods between spring and autumn.

The Sinai Peninsula is located in the northeastern portion of Egypt and is bounded by longitudes 32°20'–34°52'E and latitudes 27°45'–31°10'N. It occupies an area of about 61,000 km<sup>2</sup> or about 6% of Egypt's total area with a population of about 400,000, which is mainly Bedouin (60%) and the rest are located in small cities such as El-Arish and Sharm El-Sheikh. The Peninsula has a triangular shape; its apex is to the south at Ras Mohammed (south of latitude 28°), whereas its base is to the north extending along the Mediterranean Coast between Port Said and Rafah for about 210 km (Fig. 1). Sinai is bounded in the eastern side by the Gulf of Aqaba and the international border and in the west by the Gulf of Suez and the Suez Canal. The peninsula has over 900 km of coasts, including about 155 km along the eastern bank of the Suez Canal. Sinai history is intertwined with many societies. Previous settlers include the ancient Egyptians, Nabataea's, Romans,

Byzantines and Bedouin. Their experience in water harvesting and exploitation can teach basic lessons to the new settlers of the late twenty one century (Dames and Moore, 1982).

Rainwater harvesting can reduce the use of drinking water for landscape irrigation and sanitation. It is also an effective water conservation tool and proves more beneficial when coupled with the use of native, low-water-use and desert-adapted plants. Additionally, rainwater is available free of charge and puts no added strain on the municipal supply or private wells. Furthermore, groundwater recharge or deep drainage percolation is a hydrologic process where rainwater moves downward to the groundwater. This process usually occurs in the vadose zone below plant roots and is often expressed as a flux to the water table surface. Recharge occurs both naturally (through the water cycle) and anthropologically (i.e., artificial groundwater recharge), where rainwater and or reclaimed water is routed to the subsurface.

The concept of water harvesting as a solution for providing water to arid environments has a long history in Egypt. The northeastern coast and the North Sinai's areas have long traditions in runoff farming. Remnants from Roman times are frequently found (FAO, 1994).

Some wadi terracing structures have been in use for over centuries. In Wadi El Arish region of Egypt, stone dykes were used to direct the runoff water flow for irrigation purposes. Also cisterns, which store water for animal and human consumption as well as for supplemental irrigation, are common in Egypt. The number of cisterns has increased from less than 3,000 in 1960 to about 15,000 in 1993 with a capacity of about 4 million m<sup>3</sup> (FAO, 1994). Ironically, North Sinai has plenty of underground water and rainfall would be sufficient, if it were harvested, to support as many as a million people in the area.

In comparison with the Middle East practices, archaeological evidence of water harvesting structures appears in Jordan, Israel (Negev), Palestine, Syria and Iraq (Evenari *et al.*, 1982). Researchers have found signs of early water harvesting structures believed to have been constructed over 9000 years ago in the Edom Mountains in southern Jordan. The outstanding importance of the Middle East in the development of ancient runoff farming through water harvesting techniques is unquestioned (Pereira, 1996). The Negev's most productive period in history however, began with the arrival of the Nabataea's and other desert dwellers late in the 3rd century B.C to establish rich civilizations in the desert 2,000 years ago (Hillel, 1992; Evenari *et al.*, 1982). Runoff farming continued throughout Roman rule and reached its peak during the Byzantine era (Pereira, 1996). Water harvesting systems come in a variety of implementations, but the common components are invariably a catchment or source area, a storage facility and target or use area. For such systems the storage facility is either the soil's root zone for immediate or a small reservoir for later use.

Various studies relating the geology, geomorphology and water resources in Sinai Peninsula were helpful in our study among them: (Hammad, 1980); El Shamy (1992); GSE, 1994; FAO (1994) and Shalaby (1996).

Dames and Moore (1982) in association with the Egyptian Industrial Development Programs presented an overview of Sinai Peninsula environment taking into consideration the development potential of the peninsula's lands and water resources, with principal emphasis on the runoff potentialities of important hydrographic basins. Ahmed *et al.* (2002) reviewed the harvesting of irregular rainfall outside the Nile Valley and Delta. The review covered the hydrological, rainfall and groundwater recharge processes. The study reviewed methods of runoff harvesting, sets a framework for comparing these methods from a

technical perspective and identifies how these techniques should be applied. On the other hand, many researchers had dealt the issue of water harvesting, by using the conventional methods of surface water qualitative techniques, like investigating the relationships of geomorphometric parameters. El Shamy (1992) proposed appropriate controlling systems in Wadi El Arish hydrographic basin, which he (op. cit.) stated that the proposed structures should be started at the upstream tributaries of the hydrographic system using simple retardation stony dams. These dams are supposed to promote the groundwater recharge to the existing pervious and fractured rock formations and allow a slow controlled runoff into the downstream areas. Ashmawy *et al.* (2000) investigated the flash floods hazards of Sinai's drainage basins through analyzing the morphometric characteristics of drainage network and basins. He (op. cit.) assorted the drainage basins in respect to the possible surface runoff potentiality.

**Geomorphologic features of Sinai peninsula:** The peninsula is divided into a number of distinct geographic zones. In the north, a strip of loose sand and dunes runs inland from the coast for 16 to 32 km and then gives way to a flat, barren plain. This gravel and limestone plain continues for nearly 241 km, rising at its southern extremity to the Plateau of Gebel Al-Tih. From this plateau to the southern tip of the peninsula, Sinai is cut by a jagged system of mountains and wadies (channels that fill with water during rainstorms) (Fig. 1).

Sinai Peninsula is divided into five main geomorphologic units. These units are the southern elevated mountains, the plateau of central Sinai, the conspicuous unit of northern Sinai, mountainous and hilly areas of North Sinai and the Gulf of Suez coastal plain.

The southern part of Sinai is occupied by the high mountains complex, such as the Gebel Catherina (2,641 m amsl), Um Shomar (2,586 m amsl) and Serbal (2,070 m amsl). To the north of this mountain mass, occurs the great Egma limestone plateau, which slopes from more than 1,000 m downwards to the Mediterranean Sea. The southern mountainous is highly dissected by watersheds draining either to the Gulf of Suez or to the Gulf of Aqaba, whereas most of the drainage basins of the northern plateau are debouching northwards to the Mediterranean Sea (Fig. 1). Hydro-morphometric parameters used for determining the potential areas for RWH are given in Table 1.

Table 1: WMS hydro-morphometric output parameters used for determining the potential areas for RWH and the input criteria of the WSPM

Basin ID (Fig. 1b for locations)	Wadi (Valley) name	Basin area (km <sup>2</sup> )	Basin slope (m/m)	Basin length (m)	Average overland flow distance (m)	Max.flow distance (m)	Volume of annual flood (1000 m <sup>3</sup> ) (Finkel method)	Volume of Annual flood (m <sup>3</sup> /year) (SCS -CN method) Elewa and Qaddah, 2011)	Total runoff (m <sup>3</sup> /year) (Elewa and Qaddah, 2011)	Runoff loss by infiltration (m <sup>3</sup> /year) (SCS-CN method) (Elewa and Qaddah, 2011)
I	Eastern gulf of suez drainage system									
I-1	El Raha	440.27	0.10920	48730	782	84260	1564	3207946	5410139	2202193
I-2	Lahata	192.50	0.12292	32510	743	44628	897	658762	1184701	525939
I-3	Sudr	601.14	0.09155	53801	836	81685	1927	2315391	4268910	1953519
I-4	Wardan	1186.26	0.10579	60073	846	90161	3040	4170575	7705180	3534605
I-5	Gharandal	920.32	0.14694	57115	798	105562	2564	3925466	7202295	3276829
I-6	Tayba	356.43	0.11862	33693	875	50972	1357	1342286	2444935	1102649
I-7	Matala	119.97	0.12037	19797	863	29399	651	822791	1325254	502463
I-8	Baba	719.74	0.14152	55207	983	75483	2173	3153539	5685007	2531468
I-9	Sidri	1075.16	0.15817	79271	868	111291	2846	5749065	10748927	4999862
I-10	Feiran	1776.29	0.20014	81695	849	138938	3984	14024982	25353243	11328261
I-11	Alaawag	1924.66	0.19998	57255	969	80868	4204	13403688	24520208	11116520
I-12	Imlaha	136.83	0.13351	33797	1112	39080	712	437229	779984	342755
I-13	Isla	276.24	0.31925	45308	873	56105	1144	570850	1078629	507779
I-14	Thoman	149.93	0.26281	35915	983	42500	757	282433	543858	261425
I-15	El_Mahash	169.16	0.29427	38211	838	44896	824	362561	657802	295241
I-16	Lethei	74.46	0.14089	24443	972	28640	473	35437	84136	48699
I-17	Ghashi	106.48	0.19595	23577	1016	28474	522	51543	120364	68821
I-18	El At El Gharbi	79.77	0.10322	21421	1166	24113	495	52286	123943	71657
II	Eastern sinai drainage System (Gerafi and Gulf of Aqaba)									
II-1	Gerafi	2353.66	0.03266	71902	848	102281	4810	10643109	20055825	9412716
II-2	Watir	3522.97	0.14959	76211	822	123594	6303	1394351	12720526	11326175
II-3	Dahab	2071.41	0.22795	57586	818	96197	4416	8620926	16563557	7942631
II-4	Kid	1044.48	0.35417	47759	772	70992	2791	3851731	7187315	3335584
II-5	Umm Adawi	364.16	0.26751	36068	876	50093	1377	1068761	1933830	865069
II-6	Sasir	83.42	0.10176	19268	1117	23823	511	50138	128972	78834
II-7	El At El Sharki	107.63	0.22902	19964	905	26902	609	75217	174363	99146
II-8	Madsus	39.11	0.20526	14145	840	18368	308	23295	49546	26251
III	North sinai drainage system									
III-1	El Kharoba	1232.70	0.02167	59124	896	32382	694	8556596	15790980	7234384
III-2	El Arish									
III-2-1	El Hama El Hasana	3590.29	0.05988	85571	833	36902	640	16234425	28578308	12343883
III-2-2	El Bruk	3299.23	0.02756	90989	837	29224	602	14304144	26653440	12349296
III-2-3	Yarqa Abu Taryfya	6345.60	0.05607	138390	727	23174	495	42593062	66788359	24195297
III-2-4	El Fetahy El Aqaba	2544.64	0.04140	104550	740	17908	447	14405379	25474092	11068713
III-2-5	Geraia	3083.58	0.03718	81676	802	21253	571	16066820	28723209	12656389
III-2-6	Heridien	3905.03	0.06372	94398	871	143023	2676	14792676	26569987	11777311
III-2-7	Central Wadi El Arish	613.32	0.03362	46710	858	77870	2746	3098567	5558633	2460066
III-3	Bardawil Sector	3332.33	0.03959	64960	853	154676	1246	9309031	15888333	6579302
III-4	East Bardawil Sector	583.85	0.04291	65234	836	90078	1140	1894991	3537143	1642252
IV	Eastern suez canal drainage system									
IV-1	Salam	4453.93	0.04026	137533	822	216541	1271	20442227	32131868	11689641
IV-2	Umm Khashieb	1082.41	0.04193	87417	806	124626	1303	4888073	8641240	3753167
IV-3	El Giddi	276.98	0.05810	55069	802	76453	1600	955100	1803290	848190
IV-4	El Hagg	482.29	0.06464	57812	801	73526	1763	2526852	4321224	1794372

**MATERIALS AND METHODS**

The different stream networks and basins in Sinai were studied here to compute its hydro-morphological and hydrological parameters to assess their surface water potentialities and determining RWH effective sites. Accordingly, the present study describes a process for determining site characteristics and developing an integrated approach including Remote Sensing (RS), Geographic Information System (GIS) and Watershed Modeling System (WMS) for performing such objective.

Digital Elevation Model (DEM) with 30 m resolution of the study area has been obtained from the ASTER (Advanced Spaceborne Thermal Emission and

Reflection) (Akl, 2005), which was subsequently enhanced by the topographic contours and spot heights.

The geometric parameters of the watersheds were determined using Watershed Modeling System (WMS) software AQUAVEO, 2009, which delineates the basins and provides multiple watershed characteristics. Accordingly, nine thematic maps, viz. Volume of Annual Flood (VAF), Average Over land Flow Distance (OFD), Maximum Flow Distance (MFD), Rock or Soil Infiltration (SI), Drainage Frequency Density (DFD), Basin Area (BA), Basin Slope (BS), Basin Length (BL) and Lineaments Frequency Density (LFD) were integrated as input layers for the Weighted Spatial Probability Model (WSPM) to perform a

determination for the efficient sites suitable for the RWH. The WMS software calculated the hydro-morphometric characteristics for each watershed value used in WSPM. These values are provided for each of the delineated watersheds in Table 1. These multi layers were manipulated within the ArcGIS 9.3.3 ® software spatial analyst module (ESRI, 2009).

The geological map of Conoco, 1987 was used to extract the surface rock cover to identify the soil types. The interpretation of Enhanced Thematic Mapper Plus (ETM+) satellite image mosaic (taken in 2006) using ERDAS Imagine 9.3.1® software Leica Geosystems GIS and LLC. Mapping, 2008 had led to an additional enhancement for the extraction of lineaments.

Two runoff calculation models were used; the Soil Conservation Service-Curve Number (USDA) (1989) and the Golany (1979) methods, which were run inside the WMS 7.3 software AQUAVEO, 2009. However, the two methods have their advantages or disadvantages according the conditions of their application. Golany (1979) used his method for the Araba Valley, which was adopted in similar climatic conditions that could be similar to those of Sinai. It is a simple graphical method to determine the probability or frequency of occurrence of yearly or seasonal rainfall. On the other hand, some researchers (Hjelmfelt, 1980; Ponce and Hawkins, 1996; Fennessey *et al.*, 2001; Mishra and Singh, 2003; Geetha *et al.*, 2007; Young, 2011) have pointed out limitations and cautions to the use of the SCS-CN method for estimating runoff. The concerns include the limited regional extent (Midwestern) and landscape (agricultural) in which it was developed, discontinuous and subjective Antecedent Moisture Condition (AMC), somewhat arbitrary selection of initial abstraction and applicable size of catchment is restrictive. Accordingly, we used the two methods for runoff estimation for comparison, verification and validation purposes.

The empirical method (Golany, 1979) uses the following parameters (Eq. 1 and 2).

Peak flood flow (Qmax):

$$Q_{\max} = K_1 A^{0.67} \quad (1)$$

where, Qmax = Peak flood flows, in m<sup>3</sup>/sec

Volume of annual flood (v) in 1000 cubic meters:

$$V = K_2 A^{0.67} \quad (2)$$

where, A is the area of the basin in km<sup>2</sup> and K<sub>1</sub> and K<sub>2</sub> are constants depending on probability of occurrence:

Probability of occurrence K<sub>1</sub> & K<sub>2</sub> in a given year was taken as 10% or 1.58 & 26.5 for K<sub>1</sub> & K<sub>2</sub>, respectively.

Here we used 10 % because it is very suitable for the developmental conditions.

On the other hand, the SCS-CN model for estimating the volume of runoff (USDA 1989; Hogarth *et al.*, 2004; Jain and Sinha, 2003; Tyagi *et al.*, 2008; Elewa and Qaddah, 2011) was used. The peak flood discharge for various recurrence storm intervals of ten years in the studied watersheds using the DEM data and weighted CN generated from the existing land use and soils data was calculated by the WMS software. The major environmental factors associated with the rainfall-runoff processes are involved in the SCS-CN method. These factors include the watershed characteristics, rainfall, evaporation, evapotranspiration and runoff. The SCS-CN method is based on the water balance equation and two hypothetical equations such as the proportional equality and linear relationship between the initial abstraction and potential maximum retention (Mishra and Singh, 2003). Then the calculation of direct runoff, Q, by the SCS-CN method can be expressed as (Eq. 3):

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} = \frac{(P - 0.2S)^2}{P + 0.8S} \quad (3)$$

where, Eq. (3) is valid for P ≥ I<sub>a</sub>, Q = 0. S is determined on the CN by Eq. 4:

$$S = \frac{25,400}{CN} - 254 \quad (4)$$

Where:

P = Total rainfall in mm

I<sub>a</sub> = Initial abstraction

Q = Excess rainfall or direct runoff volume (direct runoff depth in mm)

S = Maximum potential abstraction of water by soil in mm. Potential maximum retention when runoff begins

S = Expressed in terms of a scale parameter

CN = Which can vary between 0-100 representing zero storage or 100% runoff

CN = The hydrologic soil cover complex runoff curve number (non-dimensional) (USDA, 1989)

The hydromorphometric criteria adopted in the present study to determine the suitability of different areas of Sinai Peninsula for conducting RWH are based, with modifications, on the previous similar studies, which have been found to correlate highly with peak discharge and runoff volumes (Oweis *et al.*, 2001; Morisawa, 1962; Gregory and Walling, 1973).

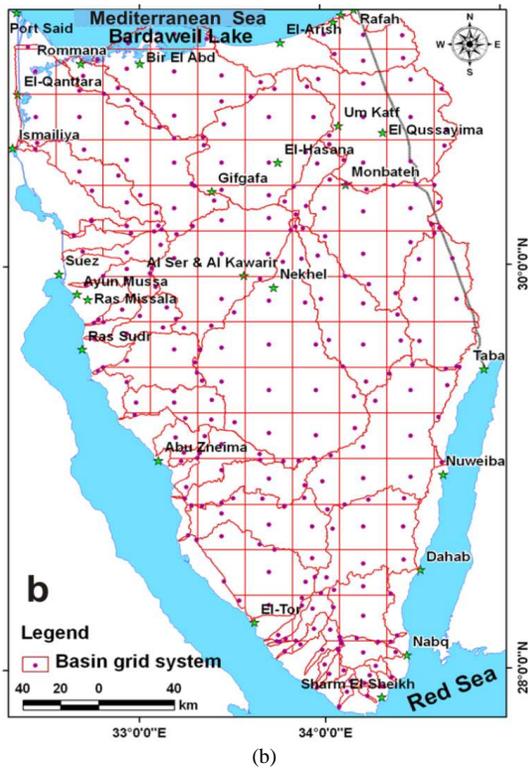
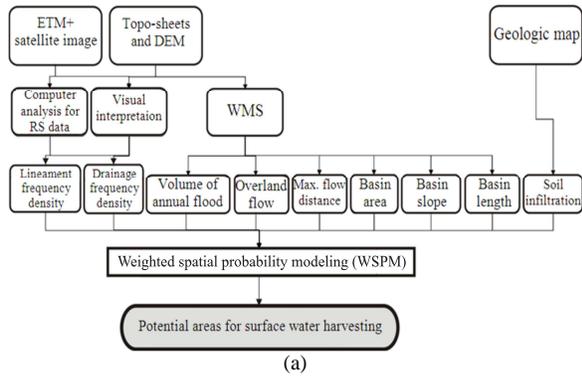


Fig. 2: a Flowchart of methodology; b Grid system (625 km ×625 km) used in mapping and WSPM techniques

The main hydromorphometric parameters deduced from the WMS include using the GIS thematic layers of VAF, OFD, MFD, SI, DFD, BA, BS, BL and LFD in performing the WSPM for determining the potential areas for RWH (Table 1). Subsequently, a Weighted Spatial Probability Model (WSPM) was constructed using the prepared multi-layer GIS, to classify the study area into four gradational rainwater harvesting (RWH) potential areas. The overall flowchart of methodology is given in Fig. 2.

## RESULTS

After defining basin attributes with the DEM inside the platform of WMS, the multi criteria decision support layers previously discussed are converted to data coverage for easier data storage and manipulation. The ranges of these input layers used in the WSPM are given in Table 2. A short description of the different parameters computed and stored in the data coverage is given below:

Integration of these criteria in the GIS-based WSPM will result in confidential maps for the efficient sites suitable for RWH, with a number of classes.

## DISCUSSION

The following is a short discussion of the nine criteria used for the construction of the WSPM maps.

**Volume of Annual Flood (VAF) criterion:** The success or failure of RWH depends to a great extent on the quantity of water that can be harvested from an area under given climatic conditions. Sinai regions vary in climate from arid-tropical, to Mediterranean and to mountain-temperate, due to its long coasts and mountains. It is generally a land of little rain. These rainfalls happen twice yearly, where they are collected in wide collectors and debouched to the wadies ended at both Gulfs of Suez and Aqaba. Essentially no summer precipitation falls in Sinai and the total precipitation falls between November and March. Here the mean number of days receiving precipitation in a year is twenty, compared to fifteen at Port Said and five at Nihil and Taba. It is generally assumed that higher mountains including Zebir, Musa and Serbal receive more than 100 mm UNESCO, 1977. The driest part of the Peninsula lies along the Plain of Qa'a. El Tor receives a scant 13 mm per year. The second driest area extends up to the coastal plain along the Gulf of Aqaba, with receipts gradually increasing from a low of approximately 15 mm at Sharm el Sheikh on the Red Sea to 20 mm at Taba near the head of the Gulf.

Data of rainfall amounts used in the calculation of VAF were compiled from the available records of published and unpublished sources (NSG, North Sinai Governorate, 2006: Environmental assessment of North Sinai, Cooperation project between Egypt and Danish Governments. unpublished, 322 pp) and Elewa and Qaddah (2011).

The VAF two thematic maps constructed by Golany (1979) and USDA (1989) methods classified the Sinai area into five classes according to their potentiality for VAF (m<sup>3</sup>/yr.).

Table 2: Ranges of input criteria used for the WSPMs

Watershed criteria	Very high	High	Moderate	Low	Very low
Basin area (Km <sup>2</sup> )	>4634	4633-3541	3540-2845	2844-1752	<1751
Basin length (m)	>97414	97413-79978	79977-72559	72558-55123	<55122
Basin slope (m/m)	<0.039	0.04-0.044	0.045-0.063	0.064-0.128	>0.129
Drainage frequency density (density/625 km <sup>2</sup> )	>222	221-162	161-121	120-61	<60
Lineament frequency density (segment/625 km <sup>2</sup> )	<3	4-6	7-13	14-29	>30
Maximum flow distance (m)	>146888	146887-100482	100481-69523	69522-48868	<48867
Average overland flow distance (m)	>1002	1001-909	908-850	849-812	< 811
Volume of annual flood (1000 m <sup>3</sup> ) (by Finkel method)	>5105	5104-3906	3905-2707	2706-1508	<1507
Volume of annual flood (m <sup>3</sup> /year) (by SCS-CN method)	>17135168	17135167-10978412	10978411-6870977	6870976-4130731	<4130730
Soil hydrologic Group (USDA, 1989)	d	c	b	a	

Table 3: Ranks and weights for criteria and their influencing classes used for RWH potentiality mapping

Data layers (Criteria)	RWH potentiality class	Average rates (Rank) (R <sub>c</sub> )	Weights (W <sub>c</sub> )	Degree of effectiveness (E)
Volume of annual flood (VAF)	I (Very high)	90	12	11.0
	II (High)	70		8.0
	III (Moderate)	50		6.0
	IV (Low)	30		4.0
	V (Very low)	10		1.0
Average Overland Flow Distance (OFD)	I (Very high)	90	11	10.0
	II (High)	70		8.0
	III (Moderate)	50		6.0
	IV (Low)	30		4.0
	V (Very low)	10		1.0
Maximum Flow Distance (MFD)	I (Very high)	90	11	10.0
	II (High)	70		8.0
	III (Moderate)	50		6.0
	IV (Low)	30		4.0
	V (Very low)	10		1.0
Rock or Soil Infiltration (SI)	I (Very high)	90	11	10.0
	II-III (High-moderate)	60		6.6
	IV (Low)	30		4.0
	V (Very low)	10		1.0
Lineament Frequency Density (LFD)	I (Very high)	90	11	10.0
	II (High)	70		8.0
	III (Moderate)	50		6.0
	IV (Low)	30		4.0
	V (Very low)	10		1.0
Drainage Frequency Density (DFD)	I (Very high)	90	11	10.0
	II (High)	70		8.0
	III (Moderate)	50		6.0
	IV (Low)	30		4.0
	V (Very low)	10		1.0
Basin Area (BA)	I (Very high)	90	11	10.0
	II (High)	70		8.0
	III (Moderate)	50		6.0
	IV (Low)	30		4.0
	V (Very low)	10		1.0
Basin Slope (BS)	I (Very high)	90	11	10.0
	II (High)	70		8.0
	III (Moderate)	50		6.0
	IV (Low)	30		4.0
	V (Very low)	10		1.0
Basin Length (BL)	I (Very high)	90	11	10.0
	II (High)	70		8.0
	III (Moderate)	50		6.0
	IV (Low)	30		4.0
	V (Very low)	10		1.0

Fig. 3a shows the classes of VAF calculated by Finkel's method, where high-very high classes (>3,906 m<sup>3</sup>/yr.) occur mostly along an axis trending SW-E-NE and parallel to the Gulf of Aqaba-International borders. They include the watersheds of Alaawag, Feiran, in the eastern

Gulf of Suez drainage System and the watersheds of Watir, Gerafi and Dahab in the Eastern Sinai Drainage System (Tables 1-2; Fig. 3a).

The moderate class (2,707-3,905 m<sup>3</sup>/yr.) of VAF is represented by the watersheds of Wardan, Sidri in the

Eastern Gulf of Suez Drainage System and the watersheds of Kid in the Eastern Sinai Drainage System. The low-very low VAF classes (< 2,706 m<sup>3</sup>/yr.) are encountered in the central-northern Sinai. The representative basins of these classes are El-Raha, Lahata, Sudr, Gharandal, Tayba, Matala, Baba, Imlaha, Isla, Thoman, El Mahash, Leithei, Ghashi, El At El Gharbi of Eastern Gulf of Suez Drainage System and the watersheds of Umm Adawi, Sasir, El At El Sharki, Madsus of the Eastern Sinai Drainage System and the watersheds of El-Kharoba, El Hamma El Hassana, El Bruk, Yarqa Abu Taryfya, El Fetahy El Aqaba, Geraia, Heridien, Bardawil Sector, East Bardawil Sector of North Sinai Drainage System.

On the other hand little shift in the spatial distribution of VAF classes was observed in case of the VAF map constructed by the SCS-CN method (1989) (Fig. 3b), where the area occupied by the very high (> 17,135,168 m<sup>3</sup>/yr.) was shrunken to a small areas in central and northwestern Sinai (i.e., a part of Wadi Abu Taryfya), whereas the high class of VAF was enlarged to comprise a larger area in north-northeastern and central Sinai. However, areas of low-very low classes occurring in north-northwestern parts encountered by Fig. 3a are replaced by the moderate-low VAF classes in Fig. 3b (Fig 3a-b; Table 1-2). This layer was assigned a weight of 12 in the WSPM (Table 3; Fig. 3a-b).

**Lineament Frequency Density (LFD) criterion:**

Lineament analysis for RWH potentiality mapping has considerable importance, where the joints and fractures enhance the rock or soil infiltration. Accordingly, the higher the LFD, the lower the RWH potentiality and vice versa.

The lineaments were extracted through the visual interpretation of the satellite ETM + data (acquired in 2006) and were confirmed by matching with the structures and lineaments indicated by the geological map Conoco, 1987. The lineament density was expressed by classifying the area into specific frames (25×25 km) and thus the number of lineaments in each grid cell was automatically counted and the resulted value was plotted in the mid-point of each cell, producing a grid map with nodes and attribute values (Fig. 2b). From the grid map, contour lines could be drawn to reflect the lineament density.

The resulting LFD map with five classes referring to the lineament density or number of lineaments per unit area (625 km<sup>2</sup>) was produced. The five LFD classes in this study were < 3, 4-6, 7-13, 14-29 and > 30 lineament/625 km<sup>2</sup>, for very high, high, moderate, low and very low for the RWH, respectively (Fig. 3c).

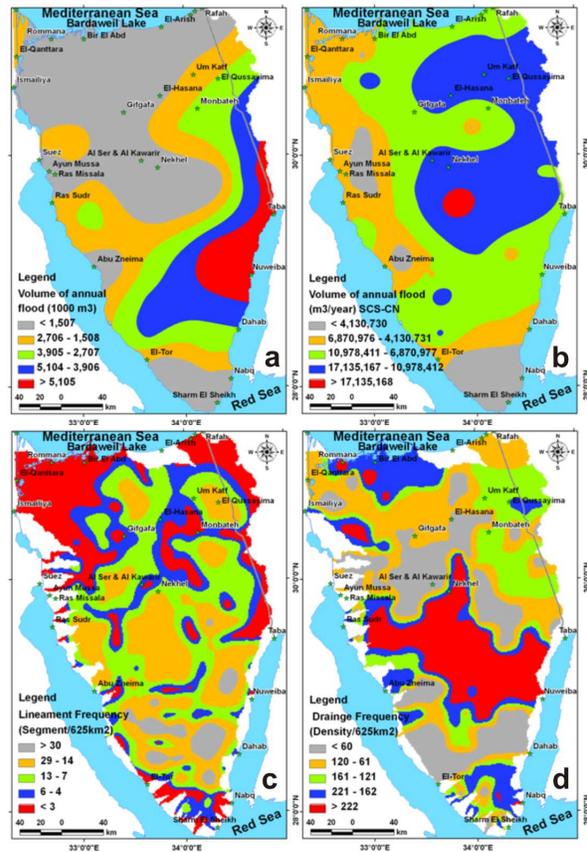


Fig. 3: GIS thematic layers used in the WSPM: a Volume of annual flood calculated by Finkel’s method (Golany, 1979); b Volume of annual flood calculated by SCS-CN method (USDA, 1989); c Lineaments frequency density; d Drainage frequency density

High-very high LFD classes (> 14/625 km<sup>2</sup>) are occurred within the fractured basement territory of southern Sinai, whereas the density decreases away from this territory towards north and south (Fig. 3c). This layer was assigned a weight of 11 in the WSPM (Table 3).

**Drainage Frequency Density (DFD) criterion:**

A map for the drainage network was prepared from the DEM of 30 m spatial resolution, topographic maps at 1:250,000 scale and satellite ETM + data (Fig. 1b).

Following the same technique and grid system used for the construction of the LFD map, a map for the DFD has been prepared, where the drainage segments were counted within the grid system (Fig. 2b).

The rate of runoff loss by infiltration is controlled by the DFD. The higher the DFD the higher the RWH potentiality and vice versa.

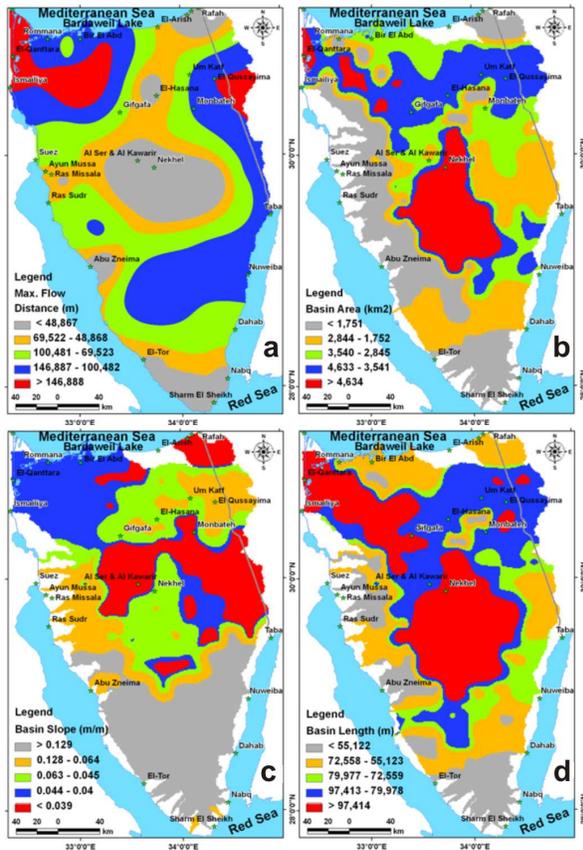


Fig. 4: GIS thematic layers of: a Maximum flow distance; b Basin area; c Basin slope; d Basin length

The resulting DFD map was also assigned to five classes by following the same approach used in preparation of the LFD map (Fig. 3d).

The DFD classes were ordered as: > 222, 221-162, 161-121, 120-61, >60 segment/625 km<sup>2</sup>, for very high, high, moderate, low and very low for RWH, respectively (Tables 1-2; Fig. 3d). This layer was given a weight of 11 in the WSPM (Table 3).

**Maximum Flow Distance (MFD) criterion:** It is defined as the Maximum Flow Distance (MFD) within a basin including both overland and channel flow (Horton, 1945). It is the maximum length of the water's path in the drainage basin (m).

This factor is important in determining the RWH capability of a drainage basin, as the higher the MFD the more chances available for RWH. It is also a function of the basin area. The constructed thematic map of the MFD criterion indicated the very high-high classes occupied the southern central-extreme eastern parts (watersheds of Watir, Sidri, Feiran, Gerafi, Heridien) with maximum flow distance ranges from 100,482 to more than 146,888 m. the very high-high

classes are also occur at the northwestern part of Sinai (i.e., Bardawil sector, Salam, Umm Khashieb), which are underlain by the old River Nile branch (the Pelusium). The very low class of the MFD is established in northern-central parts, which encompasses parts of Wadi El-Arish upstream (i.e., watersheds of El Fetahy El Aqaba, El Bruk, Yarka Abu Taryfy, El-Hamma El Hassana, El-Kharoba). Additionally, the small basins characterized by low-very low MFD classes (< 69,522 m) are also found at the extreme southern parts of the peninsula (i.e., watersheds of Umm Adawi, Sasir, El At El Sharki, El At El Gharbi, Madsus, Imlaha, Isla, Thoman, El Mahash, Lethei, Ghashi) (Fig. 1b; Table 1-2). This layer was assigned a weight of 11 in the WSPM (Table 3; Fig. 4a).

**Basin area criterion:** Basin area (A) is defined as the total area in square kilometers enclosed by the basin boundary (Horton, 1945). Basin area has been identified as the most important of all the morphometric parameters controlling catchment runoff pattern. This is because, the larger the basin, the greater the volume of rainfall it intercepts and the higher the peak discharge that result (Morisawa, 1959; Pitlick, 1994). Another reason for the high positive correlation between basin area and discharge is the fact that basin area is also highly correlated with some of the other catchment hydromorphometric characteristics which influence runoff, such as, basin length (the larger the basin, the longer its length), average overland flow distance and maximum flow distance (Gregory and Walling, 1973; Ebisemiju, 1976) and (Jain and Sinha, 2003). The thematic layer for basin area with five classes was generated (Fig. 4b). The very high basin area class (>4,634 km<sup>2</sup>) occurs in one of Wadi El-Arish upstream sub-watersheds (Yarqa Abu Taryfy) with 6345.6 km<sup>2</sup> and in some small patches at the northwestern part of Sinai in South El-Qantarra-west Bir Gifgafa area (Salam watershed). The high and moderate basin area classes (4633-2845 km<sup>2</sup>) are represented by the northern and eastern watersheds (i.e. Wadies Heridien, El-Hamma El-Hassana, part of Bardawil Sector, El-Bruk, Geraia and Watir). The low basin area class (2844-1752 km<sup>2</sup>) is represented by the watersheds of Gerafi, El Fetahy El Aqaba, Dahab and Al-Awag, which occur in eastern Sinai. The very low basin area class (<1751 km<sup>2</sup>) is represented by the watersheds of Kid, Umm Dawi, Imlaha, Isla, Thoman, El Mahash, Ghashi, Gharandal and El At El Gharbi, which occur in the extreme southern territory of Sinai. The Eastern Gulf of Suez drainage system comprises a larger portion of the very low basin area class, where it comprises the watersheds of Baha, Sudr, Lahata, El-Raha, Wardan, Gharandal, Tayba, Matala, Baba, Sidri



segregation of Sinai Peninsula into different classes with different infiltration capabilities (Fig. 5a) gave good reasons behind the spatial distribution of average OFD. Accordingly, the very low and low average OFD occurs in areas characterized by very high and high infiltration capability and vice versa (Fig. 5a-b). This layer was assigned a weight of 11 in the WSPM (Table 3; Fig. 5a).

**Rock or Soil Infiltration (SI) criterion:** The layer of rock or soil infiltration is essential to understand the nature and distribution of infiltration capabilities of surface rock units (Hasmadi *et al.*, 2010). The SI determines whether the water will infiltrate or rather runoff over the soil surface.

The classification of lithologic formations according to their infiltration capabilities or signatures was carried out depending on intensive previous investigations or previous work (NARSS, 2009 and references therein), in addition to the Soil Groups based on the USDA soil classification scheme (USDA, 1989 (Table 2)). Thus, a map with four classes was produced to reveal rock formations of similar infiltration properties or lithologic groups A, B, C and D. According to these groups, infiltration rates decrease from A to D, which is inversely related to the RWH capabilities for the same group. In the obtained classification, soil or rock groups of similar hydrologic properties were embedded in one map (Fig. 5b). The classified map with four classes was used instead of the five classes, as the SI class B includes both high and moderate infiltration capabilities. This layer was assigned a weight of 11 in the WSPM (Table 3).

**Weighted Spatial Probability Modeling (WSPM):** The Multi-Criteria Decision Support System (MCDSS) represented by the previously discussed nine thematic layers, were ranked according to their magnitude of contribution to RWH, thus they were categorized from very high to very low contribution and the same classes were used in the RWH potentiality mapping (Table 3; Fig. 6). Two WSPM were conducted, where the model was run twice; one with the VAF calculated by Finkel and the other by the SCS-CN runoff models. The model's running implied the integration of all criteria as thematic layers in the WSPM. Accordingly, two output maps will be obtained by the WSPM with a number of classes indicating the categories of RWH potentiality (e.g. high, moderate, low,). However, all the previously discussed criteria have the same magnitude of contribution on RWH potentiality, except the criterion of VAF, which has a relatively higher weight of contribution on RWH, as it represents the actual expected available runoff water to be harvested (Table 3). However, some criteria work positively while others work negatively in RWH potentiality mapping.

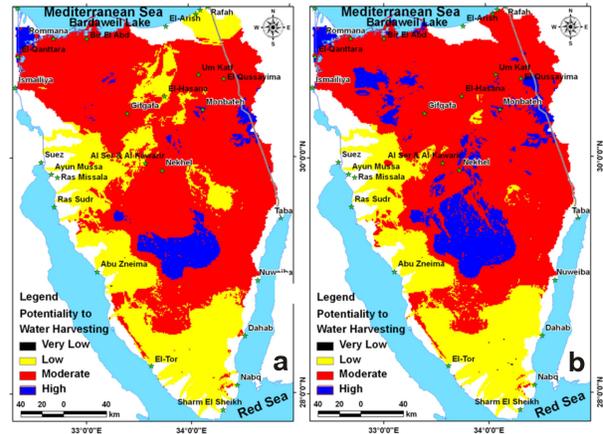


Fig. 6: WSPM maps showing the potential areas for RWH; (a) using Finkel's method for VAF calculation; (b) using SCS-CN method for VAF calculation

Consequently, the BS, LFD and SI criteria work negatively in RWH, whereas the criteria of VAF, OFD, BA, BL, DFD and MFD work positively.

The weights and rates were assumed and optimized for the multi decision support criteria depending on the experience or judgments of the authors and the opinions of experts in the previous similar works on RWH potentiality mapping (i.e., qualitative methods, for example Hasmadi *et al.* (2010); Sadrolashrafi *et al.* (2008), in addition to the geostatistical normalization and cross-validation (quantitative methods) within the ArcGIS platform before running the model (Isaaks and Srivastava (1990); Fernandez-Aviles *et al.* (2011)). The cross validation is a statistical procedure for testing the quality of a predicted data distribution and the model results. In cross validation, a piece of data whose value is known independently is removed from the dataset and the rest of the data is used to predict its value. Full cross validation is done by removing, in turn, each piece of data from the dataset and using the rest of the data to predict its value. The weights and rates were determined depending on the magnitude of contributions between each layer range of the WSPM classified layers. Accordingly, the integrated criteria were given the following weights: VAF (12%) and other parameters were given (11%). After proposing criteria weights, categorization was applied to each of the five classes among each criterion. For example, the classes graded from I (very high potential) up to V (very low potential) according to their importance in RWH potentiality mapping (Table 3).

Taking 100% as a maximum value for the rank, thus for the five classes, ranks will be classified as 100-80, 80-60, 60-40, 40-20 and 20-0%, respectively.

Table 4: Areas of RWH potentiality classes

Harvesting potentiality map (VAF calculated by Golany, 1979 method)				
Potentiality class	Very Low	Low	Moderate	High
Area (Km <sup>2</sup> )	1.38	16652.29	35923.12	3201.32
Area (% of total study area)	0.002	29.85	64.40	5.74
Total study area: 55778.11 Km <sup>2</sup>				
Harvesting potentiality map (VAF calculated by USDA, 1989 method)				
Potentiality class	Very low	Low	Moderate	High
Area (Km <sup>2</sup> )	5.57	13185.41	35896.87	6695.84
Area (% of total study area)	0.01	23.64	64.35	12.00
Total study area: 55783.69 Km <sup>2</sup>				

Consequently, the average of ranking for each class will be 90, 70, 50, 30 and 10% for classes from I-V, respectively (Table 3).

In order to calculate the degree of Effectiveness (E) for each criterion, from the criterion Weight (Wc) and criterion Rank (Rc), the weight was multiplied by the Rank (Wc × Rc). For example, if the weight of VAF equals 12% and this is multiplied by the average rank of 90, (for class I), the degree of effectiveness will be (Eq. 5):

$$E = Wc \times Rf = 0.12 \times 90 = 11 \quad (5)$$

where, as for the BA criterion, for example, the degree of effectiveness in class I will be: 90×0.11=10.

According to this method of data manipulation, assessment of the effectiveness of each decision criterion provides a comparative analysis among the different thematic layers. Therefore, it is clear from Table 3 that class I in the VAF criterion (i.e., E =11) represents the most effective criterion with regard to the RWH potentiality mapping, compared to the least influencing of class V (i.e., E=1) in all criteria.

Therefore, an arithmetic overlay approach built into ArcGIS 9.3.1 Spatial Analyst Model Builder was carried out for performing the WSPM. This overlay processing manipulates both continuous and discrete grid layers and the derived data are continuous grid data layer. Two output maps for RWH potentiality with four classes ranging from very low to high potentiality were obtained. The spatial distribution of these classes relative to the total area studied is as: 0.002 (very low), 29.85 (low), 64.40 (moderate) and 5.74% (high) for RWH potentiality map constructed using the VAF criterion calculated by the Finkel's method (Fig. 6a; Table 4) and as: 0.01 (very low), 23.64 (low), 64.35 (moderate), 12%, for the map constructed using the VAF criterion calculated by the SCS-CN method (Fig. 6b; Table 4). From these two WSPM output maps, it is clear that there is a good correlation between them.

From this point of view, the WSPM resulted in two maps that indicated the Sinai's overall moderate RWH potentiality, especially, in it's the central and northern parts. The present study confirms the results reached by

Elewa and Qaddah (2011), where they elucidated that the Sinai is characterized by an overall moderate groundwater potentiality (52.29% of its total area). This moderate groundwater potentiality class occurs within the promising areas characterized by moderate RWH potentiality class resulted from the present study. However, it is logic that the rainfall-rich watersheds are expected to be promising areas in either groundwater or runoff potentialities.

## CONCLUSION

Remote sensing, watershed modeling and GIS techniques are modern research tools that proved to be effective in mapping, investigation and modeling. These tools were used to determine the potential sites or areas for Runoff Water Harvesting (RWH) in Sinai Peninsula. The performed WSPM segregated the peninsula into four potential classes for RWH that ranges from very low to high. The areas of high potential for RWH are occupying only 5.74-12.0% (3,201-6,695 Km<sup>2</sup>), whereas the areas of low potential for RWH are existing in 23.64-29.85% (13,185-16,652 Km<sup>2</sup>) of the total Sinai's area. However, most of Sinai's area 64.35-64.40% (35,923.12-35,896.87 km<sup>2</sup>) is represented by the moderate potentiality class. For these facts and according to the overwhelming water crisis in Sinai, RWH becomes an important alternative for providing water that could be valuable for implementing runoff farming and rain-fed agriculture along the promising catchments or ephemeral streams of Sinai. Promising watersheds characterized by high and moderate RWH potentiality, i.e., Yarqa Abu Taryfya, El Hamma El Hassana, Gerafi, Watir, Geraia, Heridien, Sidri, Feiran and Alaawag, could be investigated in detail with larger scale to determine the appropriate locations for implementing the RWH structures and techniques. These studies should be performed in parallel with soil investigation to plan for some sorts of micro-catchment rain-fed-agriculture. The rain fed agriculture is already a common practice in the northern coastal areas of Sinai in Kharoba-Sheikh Zuwaid-El-Arish-Rafah strip. Additionally, RWH could

be used as a tool for flash flood hazard mitigation at the downstream by impounding water in some places upstream. The study came to a conclusion that the potential of RWH in the study area exists and implementing systems and techniques in the promising watersheds could open new opportunities for the sustainable development in the area.

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