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GIS methods for sustainable stormwater harvesting and storage using remote sensing for land cover data - location assessment

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Abstract Identification of potential sites for rainwater harvesting (RWH) is an important step toward maximizing water availability and land productivity in arid semi-arid regions. Characterised as a “water scarce” country, Egypt has limited fresh water supplies, and is expected to suffer from water stress by the year 2030. Therefore, it is important to develop any means available to supply water and maintain human habitability in a sustainable manner. Practiced or simply indispensable in many countries around the world, rainwater harvesting (RWH) promotes a sustainable and efficient manner of exploiting water resources. In the present study, suitable areas for sustainable stormwater harvesting and storage in Egypt were identified using remote sensing for land cover data - location assessment linked to a decision support system (DSS). The DSS took into consideration a combination of thematic layers such as rainfall surplus, slope, potential runoff coefficient (PRC), land cover/use, and soil texture. Taking into account five thematic layers, the spatial extents of RWH suitability areas were identified by an analytical hierarchy process (AHP). The model generated a RWH map with five categories of suitability: excellent, good, moderate, poor and unsuitable. The spatial distribution of these categories in the area investigated was such that 4.8% (47910 km^2) and 14% (139739 km^2) of the study area was classified as excellent or good in terms of RWH, respectively, while 30.1% (300439 km^2), 47.6% (474116 km^2) and 3.5% (34935 km^2) of the area were classified as moderate, unsuitable and poor, respectively. Most of the areas with excellent to good suitability had slopes of between 2% and 8% and were intensively cultivated areas. The major soil type in the excellent suitability areas was loam, while rainfall ranged from 100 to 200 mm yr^{-1}. The use of a number of RWH sites in the excellent areas is recommended to ensure successful implementation of RWH systems.

Keywords Rainwater harvesting (RWH) · Geographic information system (GIS) · Analytical hierarchy process (AHP) · Multi-Criteria Evaluation (MCE) · Decision support system (DSS)

Introduction

Rainwater harvesting provides an independent water supply during regional water restrictions and in developed countries is often used to supplement the main supply. It provides water when there is a drought, can help mitigate flooding of low-lying areas, and reduces demand on wells, which may enable ground water levels

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to be maintained. Egypt is characterised as a "water scarce" country. It has limited fresh water supplies, and is expected to be under water stress by the year 2030 (Mahmoud 2014a). Water resources distribution, misuse of water resources and inefficient surface irrigation techniques are the major problems, which have led to the country's greatest water security issues. Unlike other countries, Egypt is mostly dependent on annual rainfall in other countries to support its growing population. The source of life in Egypt over millenia, the Nile River services the country's industrial and agricultural demand. With over 2,075,600 hectares of irrigated land, Egypt has had a historically vibrant agricultural sector, (Mahmoud 2014a). However, almost all of the agricultural areas rely on the Nile for their irrigation water. Recent growth in agricultural and domestic water requirements has led to a rapid decline in the availability of water in both rural and urban areas. The search for feasible solutions to sustain water resources is, therefore, gaining considerable momentum in Egypt and elsewhere (e.g. Adamowski et al. 2012; Haidary et al. 2013), and rainwater harvesting has been promoted as one of several possible solutions. Given the limited water resources and potential increases in cultivated area, it will be necessary to develop an alternative, supplementary water source for potable and agricultural uses. It is thus useful to collect rainwater. harvest. Given the inconvenience of collecting and storing water, rainwater harvesting for long-term use was not considered as a potential source of water in the past due to a lack of understanding of its potential usefulness.

Egypt's water resources officials and legislators are facing a significant challenge due to the construction of the Grand Ethiopian Renaissance Dam. Indeed, Egyptian Irrigation Minister Mohamed Bahaa El-Din asserted on June 4, 2013 that, "the Ethiopian dam – especially during periods of water scarcity – would lead to a 'disaster' for Egypt" [http://www.diretube.com/articles/read-ethiopia-dam-could-lead-to-disaster-for-egypt_2981.html]. As the main problem facing Egypt is the scarcity of water and the absence of alternative surface water sources, promoting rainwater harvesting could help alleviate the suffering associated with severe drought conditions, a problem compounded by a rising population. Rainwater harvesting is therefore gaining importance in Egypt's water resources and agricultural development schemes.

In the past, different forms of RWH have been implemented in Middle Eastern agricultural regions, usually through diversions of spate flow from normally dry watercourses (wadi). Similar methods have been implemented in the Negev desert (Evenari et al. 1971), the desert areas of Arizona and Northwest Mexico (Zaundere et al. 1988) and in southern Tunisia (Pacey and Cullis 1986). Critchley and Reij (1989) recognized the importance of traditional, small-scale RWH systems in sub-Sahara Africa and, more recently, those associated with buildings in urban areas (Gould and Nissen-Peterson 1999).

In Egypt, some water-harvesting structures built in the Roman era have been cleaned and/or smoothed out and put back into use. At present, one or more techniques have been implemented at water harvesting sites in order to collect and store rainwater for use in meeting plant-cultivation, human and animal needs. In the 1970s and 1980s, when widespread droughts threatened agricultural production in Africa, awareness of the role of water harvesting to improve crop production was particularly heightened. Throughout the world the use of RWH can make water available in regions where other sources are too distant or too costly, and thereby supply water to small villages, households, livestock, and agriculture.

A vast array of RWH systems and structures are currently in use to address a wide variety of applications (Fewkes 1999; Gould and Nissen-Peterson 1999; Weiner 2003; Mahmoud 2014b; Mahmoud et al. 2014a; Mahmoud and Alazba 2014). The numerous advantages and benefits already ascribed to RWH (Jackson 2001; Krishna 2003; Mahmoud et al. 2014a) are sufficient to render RWH an important tool in achieving water resource management solutions under climate change (Halbe et al. 2013; Tiwari and Adamowski 2014; Adamowski et al. 2010). Identification of potential sites for RWH is an important step towards maximizing water availability and land productivity in semi-arid areas (Mbilinyi et al. 2007; Mahmoud 2014b; Mahmoud et al. 2014a; Mahmoud and Alazba 2014).

More recently, studies integrating runoff modeling, remote sensing and geographic information systems (GIS) have gained ascendance in targeting suitable sites for water recharging/harvesting structures (Mahmoud 2014b; Mahmoud et al. 2014a,b,c; Mahmoud and Alazba 2014). While there exists a great deal of literature on research and development of RWH structures, few studies exist that delineate the selection of suitable sites for water harvesting structures in arid regions using information technologies such as remote sensing (RS) and GIS. An exception to this is a study conducted in the Al-Baha region of Saudi Arabia (Mahmoud et al. 2014a) which employed remote sensing and geographical information systems (RS-GIS) to collate and analyze land use, soil, slope and hydrological digital elevation maps (DEM), along with satellite imagery (Landsat 5/7 TM/ETM) of the region. Similarly, Mahmoud et al. (2014b) presented a decision support system (DSS) for the identification of suitable sites for water harvesting/groundwater recharge structures for the Jizzan region of Saudi Arabia. Another case study was developed for the Kali sub-watershed, in Gujarat, India, as part of the Mahi River Watershed (Ramakrishnan et al. 2008). The parameters generally employed in identifying suitable sites for RWH are runoff potential, slope fracture pattern and micro-watershed area. Mbilinyi et al. (2007) presented a GIS-based DSS employing RS and a limited field survey to identify potential sites for RWH technology implementation. With the goal of improving agricultural potential characterized by low and erratic precipitation, Jabr and El-Awar (2005) presented a methodology for the localization of water harvesting reservoirs in a 300 km^2 area of Lebanon. This 3-step methodology was implemented in a Hydro Spatial Analytical Hierarchy Process (AHP) where (i) ArcGIS software served to produce pertinent spatial coverage, (ii) a Watershed Modeling System (WMS) served to simulate runoff in the watersheds, and (iii) a decision hierarchical structure employing the AHP was developed and implemented to rank various potential reservoir sites according to their suitability expressed in terms of a Reservoir Suitability Index. The outcome of this study was the excavation of a water harvesting reservoir at the outlet of the highest-ranking watershed. In developing a water harvesting strategy for the semiarid area of Rajasthan, India, Gupta et al. (1997) used a GIS approach to digitize information on the topography and soils and thus create a GIS database. Land cover information was derived from a remote sensing satellite data (IRS-1A) in the form of the normalized difference vegetation index (NDVI). Six basins were delineated using a DEM and an estimation was made of the total acreage in different slope classes. These maps were then used as input to derive a modified Soil Conservation Service (SCS) runoff curve number. Their results demonstrate the capability of GIS and its application to water harvesting planning over larger semiarid areas.

The selection of potential water harvesting areas depends on several factors including biophysical and socioeconomic conditions (Mahmoud et al. 2014a). Different studies have used different parameters in coming to such decisions: in FAO (2003), as cited by Kahinda et al. (2008), the key factors to be considered when identifying RWH sites were climate, hydrology, topography, agronomy, soils and socioeconomic criteria. Pacey and Cullis (1986) placed greater emphasis on the importance of social, economic, and environmental conditions when planning and implementing RWH projects. Using RS and GIS techniques, Ramakrishnan et al. (2008) used slope, soil porosity and permeability, runoff potential, stream order and catchment area as criteria to select suitable sites for various RWH/recharging structures in the Kali watershed, Dahod district, Gujarat, India. Similarly, Rao and Bhaumik (2003) identified land use, soil, slope, runoff potential, proximity, geology, and drainage as criteria to identify suitable sites for RWH. Kahinda et al. (2008) used physical, ecological and socioeconomic factors (land use, rainfall, and soil texture and soil depth), along with an ecological importance and sensitivity criterion.

Multi-criterion decision-making (MCDM) plays a critical role in many real-life problems (Mahmoud et al. 2014a). It is not an exaggeration to argue that almost any local or federal government, industry, or business activity involves, in one way or the other, the evaluation of a set of alternatives in terms of a set of decision criteria. Very often, these criteria are conflicting, and, even more often, the pertinent data are very expensive to collect (Triantaphyllou and Mann, 1995).

The Analytic Hierarchy Process (AHP) is a multi-criteria decision-making (MCDM) approach introduced by Saaty (1977, 1994). A type of GIS-based MCDM that combines and transforms spatial data (input) into a result decision (output), the AHP uses geographical data, the decision maker's preferences and manipulation of the data and preferences according to specified decision rules referred to as factors and constraints, respectively. Malczewski (2004) cited the considerations of critical importance in decision-making to be: (i) the GIS capabilities of data acquisition, storage, retrieval, manipulation and analysis, and (ii) the MCDM capabilities for combining the geographical data analysis and the decision maker's preferences into unidimensional values of alternative decisions.

A key decision-making tool, AHP will be used in this study to assist in obtaining appropriate solutions regarding RWH suitability assessments. Saaty (1990) noted that the AHP includes the structuring of hierarchically-selected factors, starting from the overall aim to criteria, sub-criteria and alternatives in successive levels. Saaty

(2008) outlined four steps as key factors in undertaking AHP in an organized manner in order to make a particular decision over its alternatives:

i. Definition of the issue to be considered,
ii. Identification of the goal, *i.e.*, the criteria that other elements will depend upon, and which should be at the top of the decision-making tree,
iii. Development of a pairwise comparison matrix,
iv. Priority weighting for each element, drawing upon priorities obtained in the comparison matrix, to obtain the priorities that will form the basis of decision-making regarding alternatives at the bottom of the hierarchy.

Most studies have focused on the selection of sites for rainwater harvesting in rural or urban areas such as the study conducted by Inamdar et al. (2013) to develop a robust GIS based screening methodology for identifying potentially suitable stormwater harvesting sites in urban areas. In an urban setting, harvesting is usually done with the help of some infrastructure or the simplest method for a rainwater harvesting system is storage tanks. In this approach, a catchment area for the water is directly linked to cisterns, tanks and reservoirs. However, at a national level, limited resources are allocated for applying rainwater harvesting (RWH) technology. Therefore, the purpose of this study was to delineate potentially-suitable areas for sustainable stormwater harvesting and storage in Egypt using using remote sensing for land cover data - location assessment. First, a national map of RWH availability was generated, with which Egypt's decision-makers and water resources planners could choose suitable locations for rainwater-harvesting structures, and then make an assessment of the most suitable sites for RWH for the entire country. Moreover, this study will help to restore natural stream channels and floodways within urban areas to secure economies, retard discharges, reduce peak flows, and enhance the interception of suspended solids and nutrients, and to maximize the use of rainfall water and open space and landscape values. Control is required over the rate of sediment deposition, to ensure the viability of grass and other ground covers.

Framework for RWH mapping

Implementing the present research study required efforts in different disciplines: office work, a field survey, application of various models, and an assortment of supporting techniques (e.g., use of GIS, RS, and aerial images). A field survey was conducted between June and July 2011 and from June to August 2012. Fieldwork included geomorphological, land cover mapping and GPS-based observations of soil textures. The data was processed using Erdas Imagine 2013, IDRISI Selva 17 and ArcGIS 10.1 software. The identification of suitable areas for RWH is a multi-objective and multi-criterion problem. The mapping methodology employed in this study involved the following major steps:

i. Selection of criteria,
ii. Assessment of suitability level of criteria for RWH,
iii. Assignments of weights to these criteria,
iv. Collection of spatial data to address the criteria, including a GPS survey to supplement and generate maps using GIS tools,
v. Development of a GIS-based suitability model, which combines maps through a Spatial Multi Criteria Evaluation (SMCE) process, and
vi. Generation of suitability maps.

The five criteria selected for the identification of potential sites for RWH [soil type, land cover/land use, slope (topography), run off coefficient, and rainfall surplus precipitation] are presented in a work flow chart (Figure 1). Because of the different scales on which the criteria are measured, the SMCE requires that the values contained in the criterion map be converted into comparable units. Therefore, the criteria maps were reclassed into 5 comparable units or 'suitability classes': 5 ("excellent"), 4 ("good"), 3("moderate"), 2 ("unsuitable") and 1 ("poor"). The suitability classes were then used as a basis to generate the criteria map. The methodology used to determine the potential RWH sites for the study area using RS and GIS are illustrated in a flow chart (Figure 1).

Study area

Egypt is situated in the Northeastern corner of the African continent, and has a total area of approximately 1×10^6 km^2.The Egyptian terrain consists of a vast desert plateau interrupted by the Nile Valley and Delta, which occupy about 4 percent of the country's total area. The land surface rises on both sides of the valley reaching about 1000 m above sea level in the east and about 800 m above sea level in the west. The country's highest

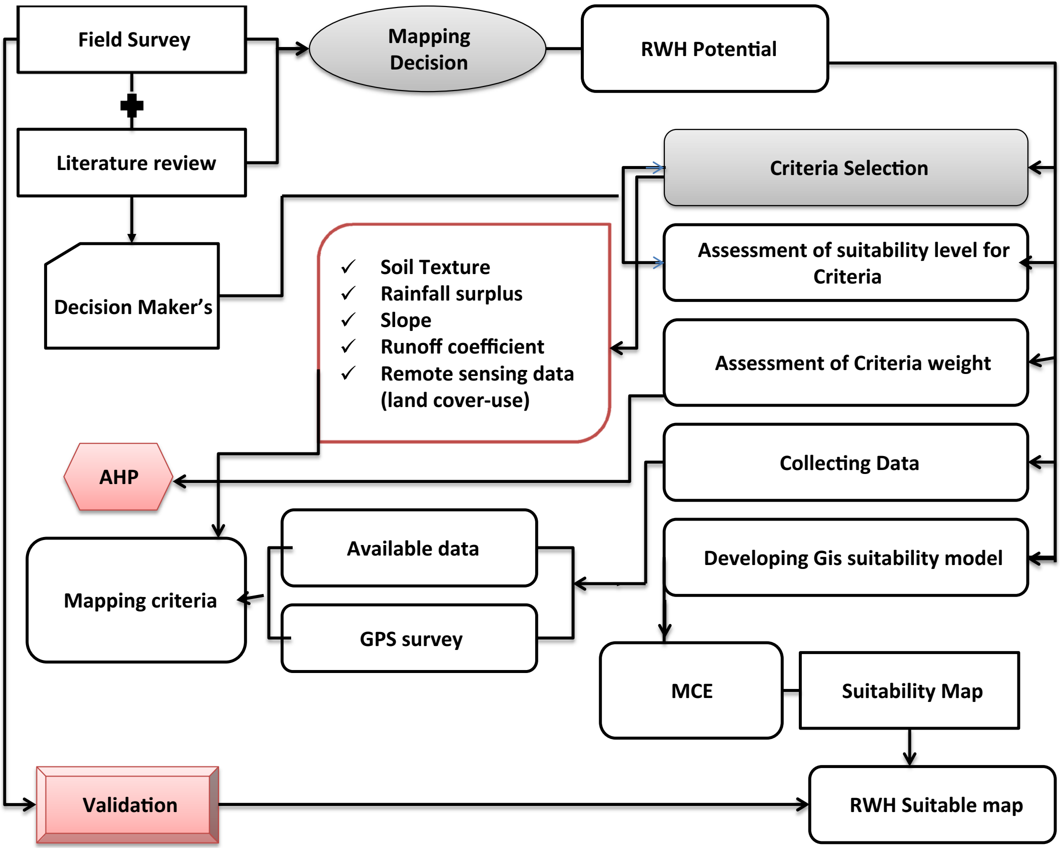

Fig. 1 Conceptual framework of RWH potential mapping

point, located at Mount Catherine in the Sinai, is 2629 m above sea level and the lowest point, at the Qattara Depression in the northwest, is 133 m below mean sea level. The majority of the country's expanse is desert land. Most of the cultivated land is located close to the banks of the Nile River, its main branches and canals, and in the Nile Delta. Rangeland is restricted to a narrow strip, only a few kilometres wide, along the Mediterranean coast and its bearing capacity is quite low. There is no forestland. The total cultivated area (arable land plus permanent crops) is 3.4 million hectares (ha) (2002), or about 3% of the nation's total area. Arable land accounts for about 2.9 million ha, or 85% of the total cultivated area, while permanent crops occupy the remaining 0.5 million ha. Hot dry summers and mild winters characterize Egypt's climate. Rainfall is very low, irregular and unpredictable. Annual rainfall ranges from a maximum of about 200 mm in the northern coastal region to a minimum of near zero in the south, with a national annual average of 51 mm. Summer temperatures are extremely high, reaching 38°C to 43°C with extremes as high as 49°C in the southern and western deserts. The northern areas on the Mediterranean coast are much cooler, with 32°C as a maximum.

Water resources in Egypt

The Egyptian territory comprises the following river basins (Mahmoud 2014a):

- The Northern Interior Basin is located in Egypt's east and southeast, covering 520,881 km^2 or 52% of the country's total area. The Qattara Depression is a sub-basin of the Northern Interior Basin.
- The Nile Basin, covering 326,751 km^2 (33%), located in the central part of the country, occurs in the form of a broad north-south strip.
- The Mediterranean Coast Basin, covering 65,568 km^2 (6%).
- The Northeast Coast Basin, a narrow strip of 88,250 km^2 along the coast of the Red Sea (8%).

The River Nile is Egypt's main source of water, with an annual allocated flow of 55.5 $km^3\ yr^{-1}$ under the Nile Waters Agreement of 1959. Internal surface water resources are estimated at 0.5 $km^3\ yr^{-1}$, bringing the total actual surface water resources to 56 $km^3\ yr^{-1}$. The Nubian Sandstone aquifer located under the Western Desert is considered an important groundwater source. The volume of groundwater entering the country from the Libyan Arab Jamahiriya is estimated at 1 $km^3\ yr^{-1}$. Internal renewable groundwater resources are estimated at 1.3 $km^3\ yr^{-1}$, bringing the total renewable groundwater resources to 2.3 $km^3\ yr^{-1}$. The main source of internal recharge is percolation from irrigation water in the valley and the delta.

Data input and processing

Soils map

A soils map of Egypt was obtained from the FAO World Soil Resources report (1978), by extracting it from the World Soils Map. Soil associations are indicated on the original maps by the symbol of the dominant soil unit, followed by a number, which refers to a descriptive legend on the back of the map, where the full composition of the association is given. Associations in which Lithosols are dominant are marked by the Lithosols symbol I combined with one or two associated soil units or inclusions; where there are no associated soils, the symbol I alone is used. The legend of the original World Soil Map (FAO 1974) comprises an estimated 4,930 different map units, consisting of soil units or associations of soil units. When a map unit is not homogeneous, it is composed of a dominant soil and component soils. The latter are: associated soils, covering at least 20 percent of the area; and inclusions, important soils which cover less than 20 percent of the area. The soil maps were classified into two classes: loam and sand (Figure 2). Loamy soil has a moderate infiltration rate when it is thoroughly wetted, and classified as mainly showing moderately deep infiltration, moderately to-well drained soils with moderately fine to moderately coarse textures. In comparison, sandy soils have a higher infiltration rate.

Verification of existing soil maps and improving the quality of information on soil maps

During the soil mapping fieldwork, site descriptions were obtained and soil types were identified by recognising and grouping similar sites. Observation sites were used solely within areas which failed the obvious landscape requirements (*i.e.*, slope, rock outcrop, surface rockiness). The following data were collected at each site:

- Unique identification;
- Location (provided as geographical position system (GPS) recorded coordinates);
- Required attribute values for slope, rockiness; and
- Landscape photograph clearly labelled with the unique site identification, photo direction and the landscape or soil feature being assessed.

Soil samples were collected in accordance with sampling protocols outlined in Ryan and Wilson (2008). Recommended sampling depths were 0-50 mm, 50-150 mm, 150-300 mm, 300-600 mm and 600-1000 mm. A 50 mm diameter push tube was used for collecting these samples. All samples were identified by a qualified soil scientist using the project name, unique profile number and depth range from where the sample was taken.

The location of detailed sites was representative of the soil type being assessed and with attributes that are typical for that soil. It was considered desirable that the soil type name from any existing soil survey or soil map be used, provided the observed soil could be correlated to the published soil type.

Verification sites were examined in sufficient detail to allocate the site to a soil type and soil map unit. As verification sites are commonly used to accurately position the boundaries of soil map units, to describe the variability within a soil map unit and to validate soil predictions, the verification sites served to investigate the accuracy and relevance of the existing mapping within the assessment area. As a result of the verification process, the verification sites largely confirmed the existing mapping; therefore, the existing soil map units were sufficient to support a RWH assessment. However, if the on-ground assessment showed inconsistencies or errors in the available information, then a more detailed site description and mapping would be required.

Land cover and land use

A Landsat 5/7 TM/ETM image incorporated with field-collected data served in categorizing land use and land cover (LULC). This image was geometrically corrected and projected to the World Geodetic System (WGS 84—UTM zone 37N). The Landsat images were

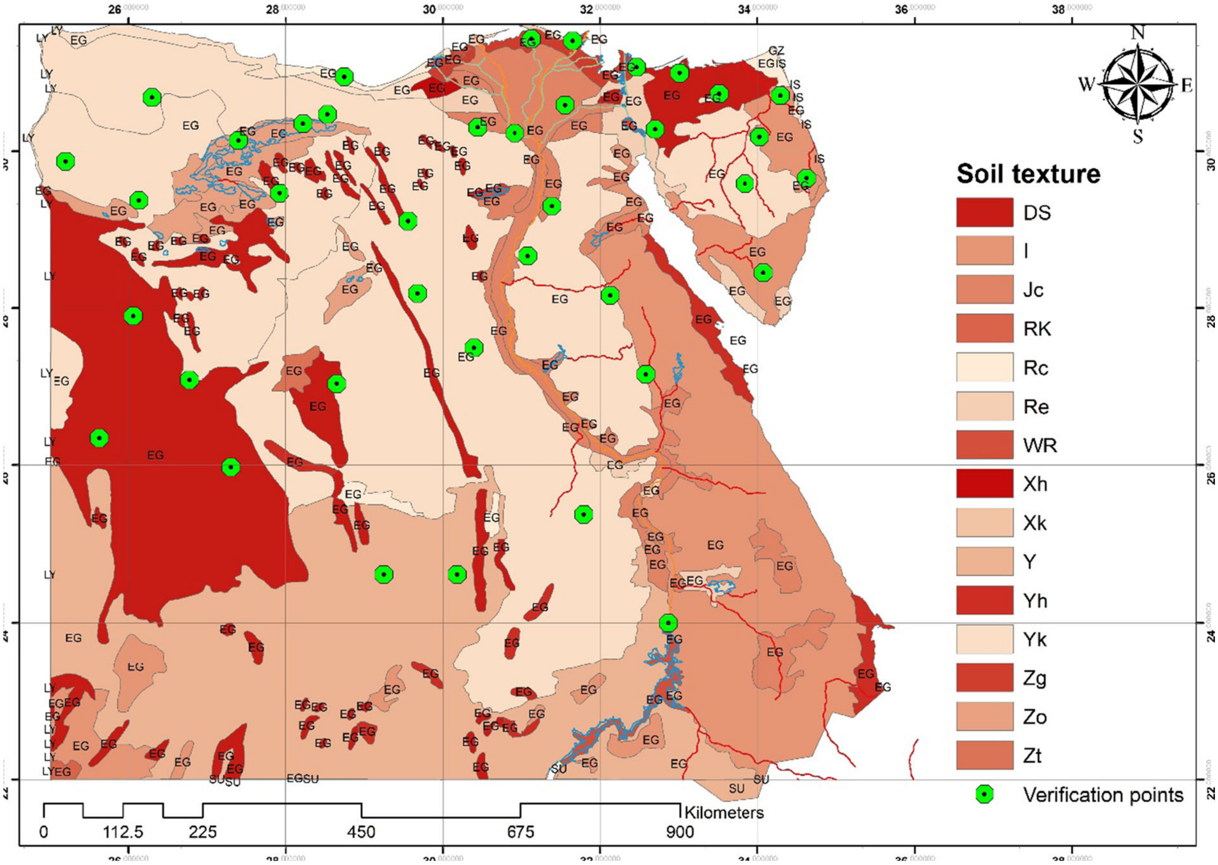

Fig. 2 Soil texture map for the study area

resampled using the nearest neighbour algorithm to keep the original brightness and pixel values. The resultant root mean squared error of this image was less than 0.65 pixel. The Cost model in IDRISI Selva was used for the atmospheric correction. Using the technique of image normalization, Landsat images were then indirectly normalized for atmospheric absorption after identifying 12 PIFs, and a linear regression was then used to place the data at each band onto the same radiometric reference. Image classification was performed using the Iso Cluster Unsupervised Classification tool in ArcGIS 10.1 Spatial Analyst to define the signature files and fix the number of classes. The resulting raster layer provided delineation of the land cover classes in the satellite images. Classes with a similar value were merged. Unsupervised classification revealed four land cover classes, which were then verified by training ssamples collected during the field surveys to create spectral signatures (i.e. reflectance values). Using the maximum likelihood classification method and the previous collected ground data, we identified what each cluster represented (e.g. water, bare earth, dry soil, etc.). The classification accuracy of the classified images was determined by both simple random and stratified random patterns. The simple random pattern provides an equivalent probability of sampling over the entire study area with no operator bias. To achieve this, 125 reference pixels were used for accuracy assessment, resulting in a 96% accuracy with an acceptable error of 4%. The resampling function in IDRISI Selva was used to improve the resolution and accuracy of the images in this study. During the field survey, visualization of the specific land cover was made to collect ground truth points for classification and to visualize human impact on land cover changes. More than 500 ground truth points were taken during the two field surveys. The land cover classification was based on ground truth points using geocoded ground observation points and visual interpretation of Google Earth images. The LULC map classified the territory into 15 main classes (Fig 3). The area contributed by each type of land cover and land is presented in Table 1.

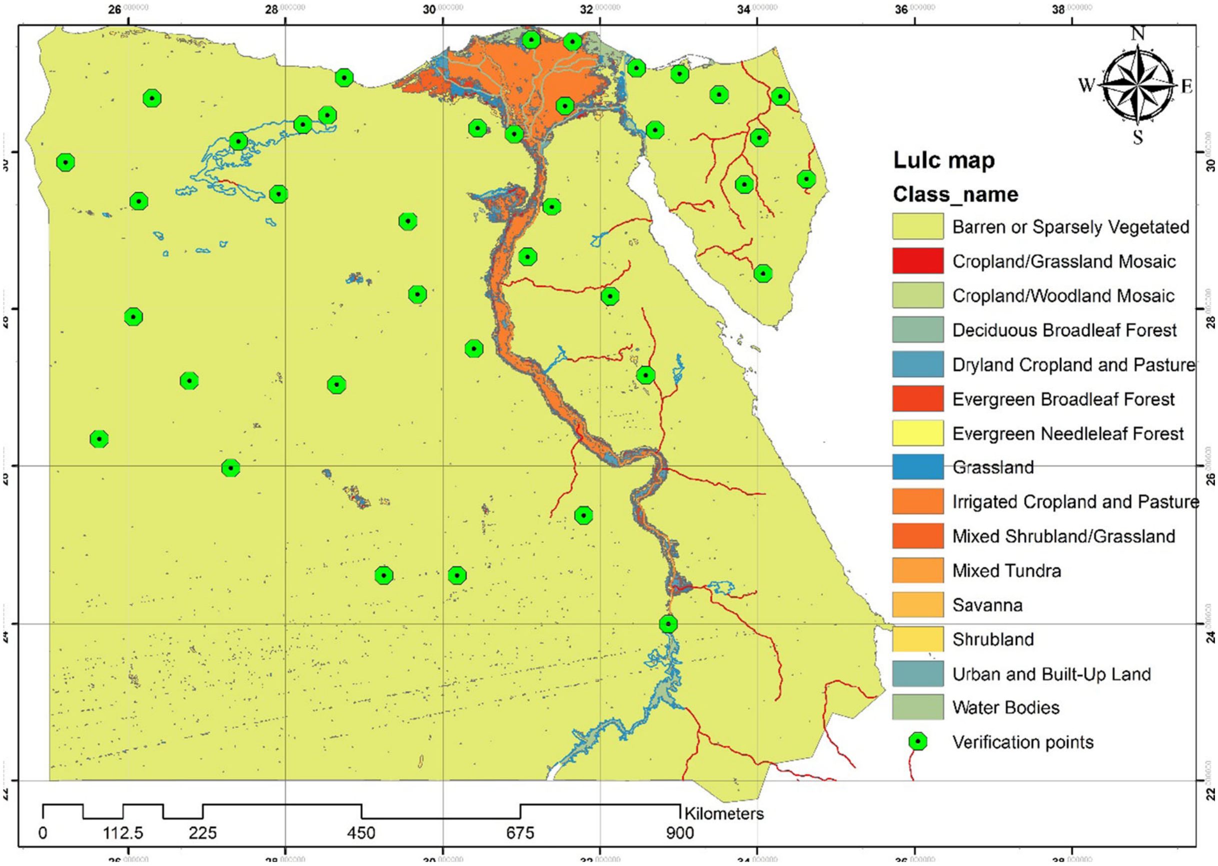

Fig. 3 Classified land cover and land use map for Egypt

Table 1 shows the different land cover and land use classes in a study area where 'Barren or Sparsely Vegetated' land represent the largest portion of the area (95.03%), and only 2.08% of the total area are 'Irrigated

Table 1 Areas covered by the different land cover and land use

Class number	Class name	Area (km^2)	% of total area
1	Barren or sparsely vegetated	950,288	95.03
2	Cropland/grassland mosaic	1864	0.19
3	Cropland/woodland mosaic	330	0.03
4	Deciduous broadleaf forest	163	0.02
5	Dryland cropland and pasture	4386	0.44
6	Evergreen broadleaf forest	2133	0.21
7	Evergreen needle leaf forest	40	0.00
8	Grassland	4286	0.43
9	Irrigated cropland and pasture	20,756	2.08
10	Mixed shrubland/grassland	2641	0.26
11	Mixed tundra	1	0.00
12	Savanna	2329	0.23
13	Shrubland	4111	0.41
14	Urban and built-up land	486	0.05
15	Water bodies	6217	0.62

Cropland and Pasture.' Water bodies represent 0.62 % of the total area (Table 1) and represent fixed water sources.

Assessing the accuracy of a land cover map requires on-site observation of a sample of points or areal units. Ground truthing points collected using GPS served to validate the developed land cover and land use map (Figure 4). Validation analysis was performed using the Kappa Agreement Index (KIA). A Kappa index exceeding 0.8 indicates a high classification performance (Jensen 2005). The overall kappa statistic was 0.825, indicating that the classification of land use and land cover was accurate.

Slope (topography)

A 30 m resolution DEM was used to generate a slope map for Egypt. The DEM was analyzed to remove sinks and flat areas to maintain continuity of flow to the catchment outlets. A GIS was used for DEM preparation by filling in sink areas so the DEM was ready for the next step (Figure 4). The slope map (Figure 5) for the study area was generated from the filled DEM map of Egypt. In this study, the slope map was reclassified into five classes based on the FAO classification (FAO 2006) namely 0-2% is flat; 2-8% is undulating; 8-15% is rolling; 15-30% is hilly; > 30% is mountainous and is assigned different suitability rank.

Potential runoff coefficient

The curve number (CN) is a hydrologic parameter used to describe stormwater runoff potential for a given drainage area. It is a function of land use, soil type, and soil moisture. Mahmoud et al. (2014c) used satellite imagery of the Al-Baha region as well as land cover/use maps, and soil maps of the region processed through a GIS to determine the potential runoff coefficient (PRC) in the Al-Baha region of Saudi Arabia. Similarly, Mahmoud (2014a), using a GIS, estimated PRC values varying from 0.03 to 1.0 for different regions of Egypt based on their hydrologic soil group (HSG), land use,

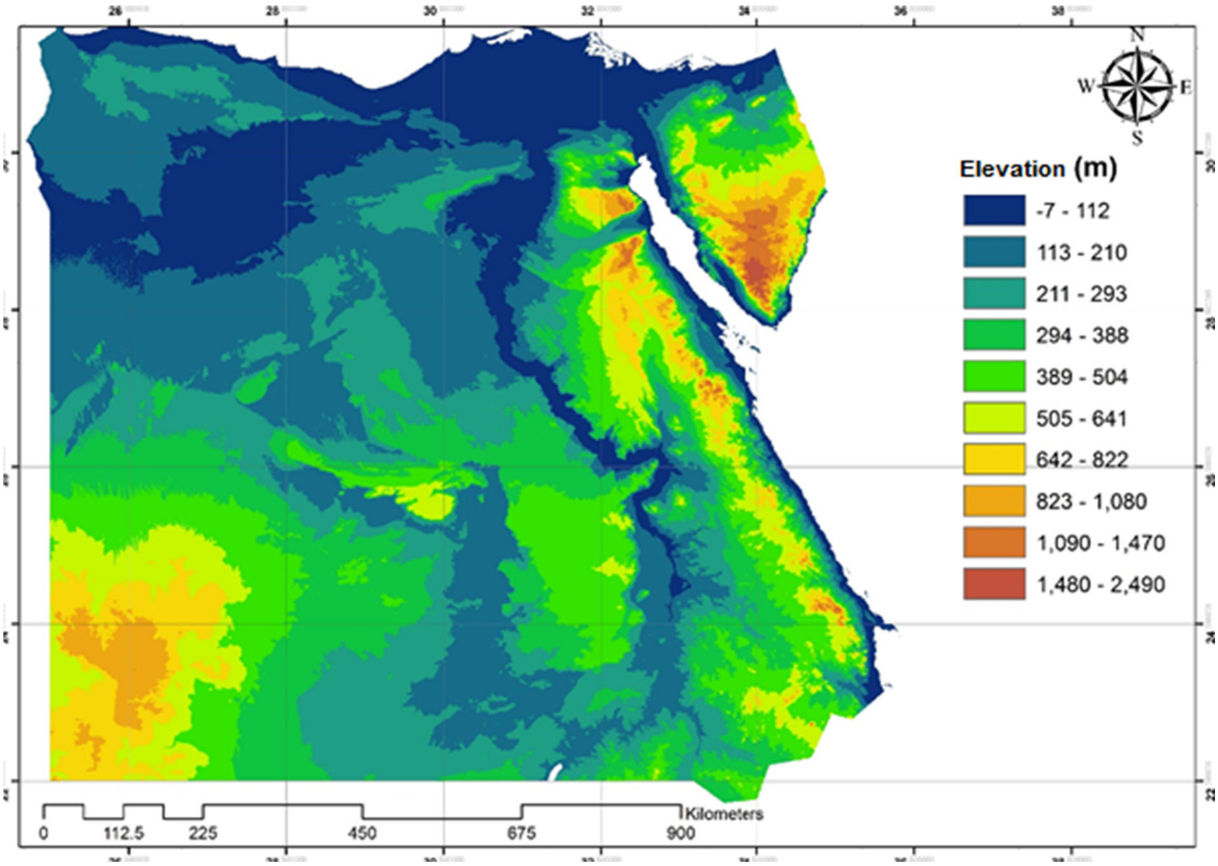

Fig. 4 The exploitation of digital elevation model for Egypt

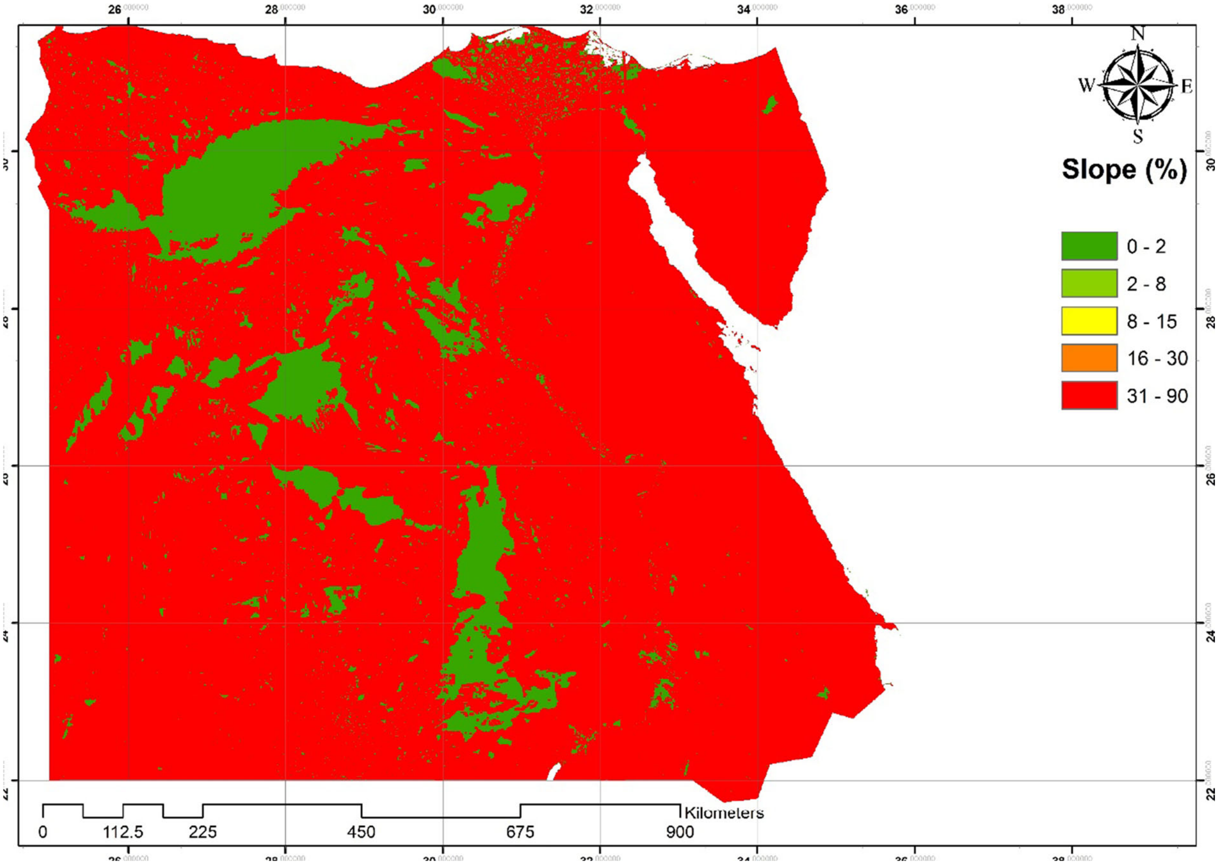

Fig. 5 Slope map for identifying potential rainwater harvesting sites

slope, and measured runoff volume (Figure 6) These values indicate the potential amount of annual rainfall that can be harvested and used for agriculture, potable water and groundwater recharge. If harvested, this water would represent an additional water source for Egypt. Moreover, areas with higher runoff potential are suitable locations to set up successful rainwater harvesting works to retain the water.

The PRC approaches 0 when the slope is very small (approx. 0°) and 1 when the slope is infinite (90°). The magnitude of change in PRC decreases with increasing surface slope, confirming that runoff volume for a given quantity of rainfall is less or unchanged by slope beyond a critical slope (Sharma 1986; Mahmoud et al. 2014a, c; Mahmoud 2014a,b).

Rainfall surplus

The amount of rainfall at different locations in Egypt was collected for a period of 31 years. The data indicated that rainfall in Egypt was very scarce, with an annual average of 12 mm and a range of 0 mm y^{-1} in the desert to 200 mm y^{-1} in the north coastal region. The maximum total amount of rain across the country does not exceed 1.8×10^9 m^3 y^{-1}. However, the mean rainfall water effectively used for agricultural purposes totals 1.0×10^9 m^3 y^{-1} Mahmoud (2014a). Climatic data obtained from the meteorological department of the Ministry of Agriculture was interpolated by using the following sources:

1. Satellite images for monthly global precipitation from 1979 to 2009 obtained from the World Data Center for Meteorology.
2. NASA Tropical Rainfall Measuring Mission (TRMM) Monthly Global Precipitation Data from 1998-2010 obtained from the NASA GES Distributed Active Archive Center.

The Penman-Monteith method (Monteith, 1965) was used to estimate the potential ET:

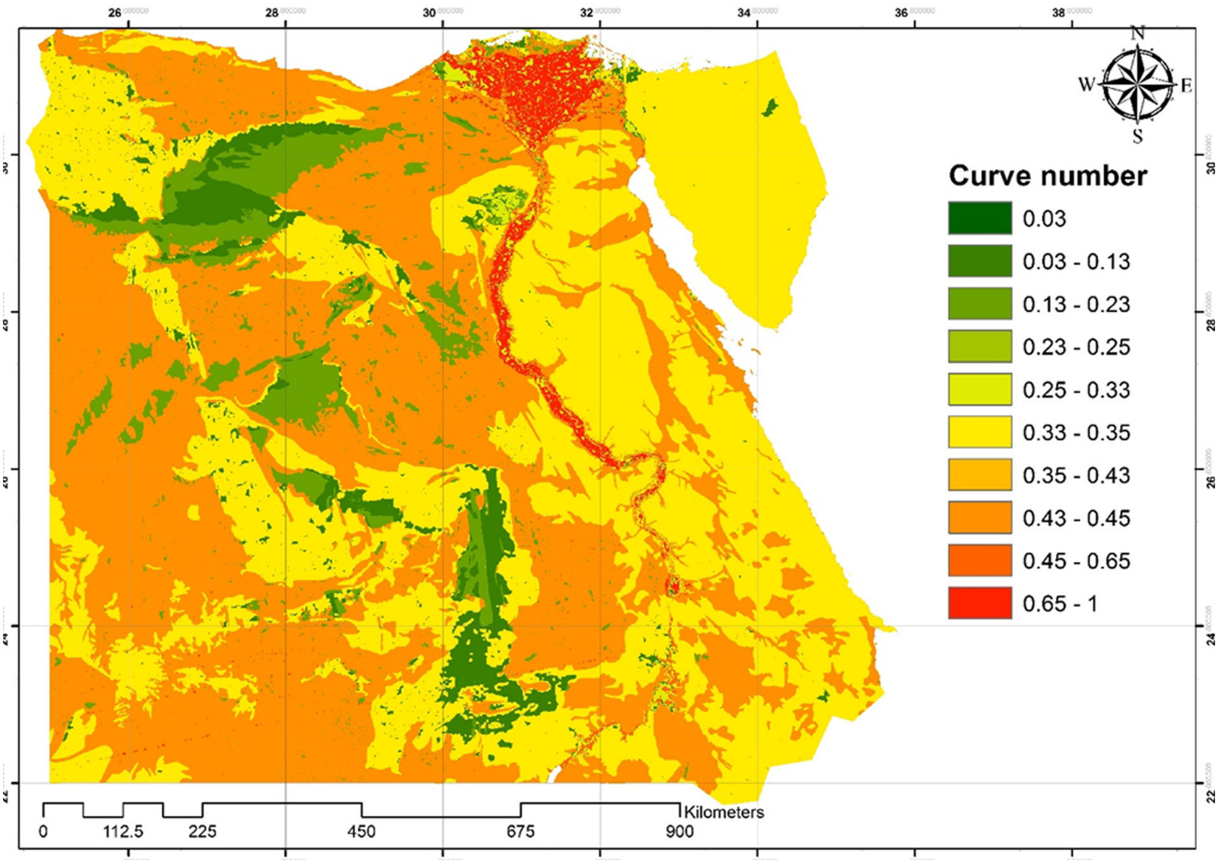

Fig. 6 Distribution of potential runoff coefficient (Mahmoud 2014a)

$$E_T = \frac{\Delta R_n + (e_a - e_d) * \frac{\rho * c_p}{r_a}}{\lambda\left(\Delta + \gamma * \left(1 + \frac{r_s}{r_a}\right)\right)}$$ (Adamowski et al., 2010)

where

R_n = net radiation (W/m^2);

ρ = density of air;

c_p = specific heat of air;

r_s = net resistance to diffusion through surfaces of leaves and soil (s/m);

r_a = net resistance to diffusion through the air from surfaces to the height of the measuring instruments (s/m);

γ = hygrometric constant;

Δ = de/dT;

e_a = saturated vapour pressure at air temperature; and

e_d = mean vapour pressure.

ET refers to the total amount of water vapor entering into the atmosphere through either the evaporation of water from open water and soil surface or transpiration of water from vegetation leaves. Estimating ET has been a significant scientific challenge for many years until Penman (1948) proposed the combination approach, which solved the problem for open water or wet soil surface. Penman (1953) further improved the model for unsaturated surfaces of single leaves by introducing resistance. Monteith (1965) applied the Penman equation for the canopy. The Penman equation then became the well-known Penman-Monteith equation. The amount of ET is equally expressed in two units: the amount of water left on the surface in ET (mm) or the amount of energy used in ET (W/m^2).

A rainfall surplus (P-ET) map was developed by subtracting long-term average monthly evapotranspiration from precipitation values for all meteorological stations over the period of 1950 to 2012. In areas where there is excess rainfall, the surplus rainwater can be used to recharge ground water through artificial recharge techniques. In the present study, the annual rainfall surplus calculated at each meteorological station was obtained by adding only the positive values of the difference (P-ET), and by interpolating previous data values using ArcGIS, generating a map of the spatial distribution of rainfall surplus (Figure 7).

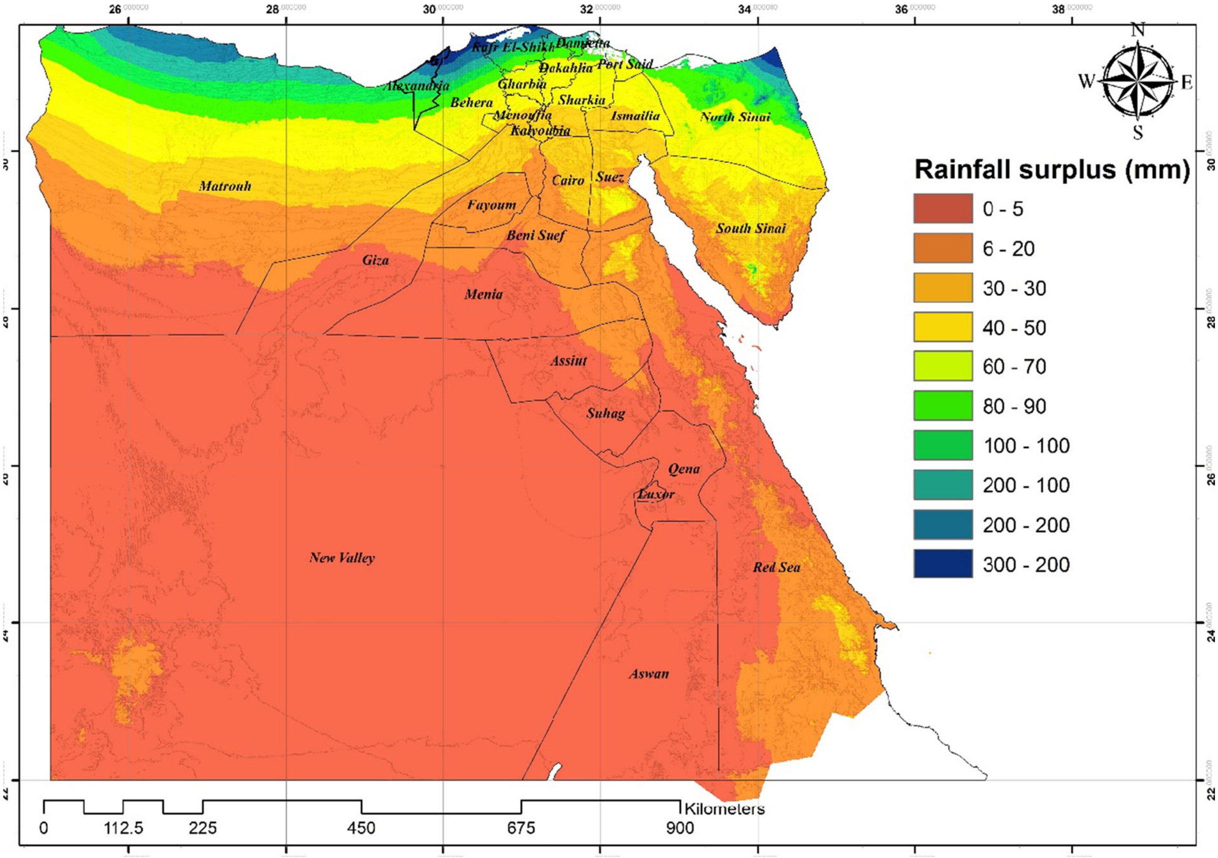

Fig. 7 Rainfall surplus map for the study area

Rainfall surplus will not underestimate rainwater harvesting for irrigation or domestic uses, as the main source of irrigation in Egypt is the Nile River. In addition, the amount of rainfall ranges from 0 to 200 mm per year. Therefore, in any case it will not affect the designed amount of water use because it will only be used to remove some burden of the required water for different uses from the Nile River or groundwater. When precipitation values are in excess of the potential evapotranspiration, especially for regions having poor infiltration capacity of soils, there is the danger of flood and accelerated erosion. In general, moisture from rainfall is critical during the shorter rainy season and thus it can never help to harvest the major crops, as it does not satisfy the crop water requirements of those crops. However, the moisture during this period could be used to facilitate land preparation activities for early planting in the main rainy season and this subsequently saves

Table 2 Suitability ranking for soil texture (Mahmoud et.al 2014b)

No.	Soil texture class	RWH suitability
1	Fine	5
2	Fine and medium	4
3	Medium	3
4	Medium and coarse	2
5	Coarse	1

Table 3 Suitability ranking for rainfall surplus (Mahmoud et.al 2014b)

No.	Rainfall surplus class	RWH suitability
1	Very large deficit	1
2	Large deficit	2
3	Medium deficit	3
4	Small surplus	4
5	Large surplus	5

Table 4 Suitability ranking for slope (FAO, 2006)

No.	Slope class	Slope %	RWH suitability
1	Flat	0–2	3
2	Sloping	2–8	5
3	Strongly sloping	8–15	4
4	Moderately steep	15–30	2
5	Mountainous	>30	1

Table 6 Suitability ranking for RC (Mahmoud et.al 2014b)

Runoff index	RWH suitability
0–0.03	1
0.03–0.23	2
0.23–0.45	3
0.45–0.65	4
0.65–0.1	5

time and moisture that could have been used from the main cropping season.

Towards the south of the country, rainfall tapers off very rapidly to less than 20 mm y^{-1} per year, and shows great year-to-year fluctuation (Figure 7). One of the main issues is to increase the efficiency of runoff water use for human and animal consumption and cultivation, and to minimize soil erosion. This is possible because the area's geography and hydrology are ideal for effective use of water harvesting systems.

Results and discussion

Assessment of suitability level of criteria for RWH

Based on a review of the literature and expert opinion, the suitability criteria for RWH were developed with regard to soil texture, rainfall surplus, slope, land cover, and PRC (Tables 2, 3, 4, 5 and 6, respectively). Obviously, areas with a large rainfall surplus will have a high suitability rank as the surplus ensures the availability of runoff to be harvested. While RWH structures are generally more appropriate in areas having a smaller slope, a slight slope is needed for better runoff harvesting. The ground slope is a key limiting factor to water harvesting. In-situ RWH is not recommended for areas where slopes are greater than 5% due to the uneven distribution of runoff and large quantities of earthwork required which is not economical. Pond areas with slopes ranging from 2 to 8% are more appropriate (Critchley and Siegert 1991). Therefore, slopes ranging from 2 to 8% were given a higher suitability rank. A PRC exceeding 0.5 was considered best (Mahmoud 2014b)

Assignments of weights to criteria

Weights were assigned to the criteria by applying pairwise ranking and rank sum methods. The final weight calculation requires the computation of the principal eigenvector of the pairwise comparison matrix to produce a best-fit set of weights. The weight module of IDRISI software (Eastman 2012) was used for this calculation. The IDRISI weighting procedure is based on AHP, a multi-factor decision making (MFDM) method that helps the decision-maker facing a complex problem with multiple conflicting and subjective factors (for example location or investment selection, project ranking and so forth). The pairwise comparison approach is used in IDRISI to assess weights for evaluation criteria (factor maps) in GIS-based decision making. This method has been tested theoretically and empirically for a variety of decision situations, including spatial decision-making. Several studies have demonstrated the usefulness of AHP in a wide range of fields (Zahedi 1986; Vargas 1990; Forman and Gass 2001; Kumar and Vaidya 2006; Hossain et al, 2007; Wang et al, 2009;

Table 5 Suitability ranking for land cover (Mahmoud et.al. 2014b)

No.	Land cover type	Land cover class	RWH suitability
1	Intensively cultivated	Very high	5
2	Moderately cultivated	High	4
3	Forest, exposed surface	Medium	3
4	Mountain	Low	2
5	Water body, urban areas	Very low	Restricted

Table 7 Importance ranking of pairwise combination of factors

Level of importance	Definition	Explanation
1	Equal importance	Two activities contribute to the objects
2	Weak or slight	
3	Moderate importance	Experience and judgment slightly prefer one activity over another
4	Moderate plus	
5	Strong important	
6	Strong plus	
7	Demonstrated	An activity is favored very strongly over another; its dominance is demonstrated in practice
8	Very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity *i* has one of the above non-zero numbers assigned to it when compared with activity then *j* has the reciprocal value when compared with *i*	A reasonable assumption
1.1–1.9	If the activities are very close	May be difficult to assign the best value but when compared with others contrasting activities. The size of the small numbers would not be noticeable, yet they can still indicate the relative importance of the activities

Young et al. 2010; Garfi et al. 2011; Anane et al. 2012; Mahmoud 2014b).

The first step was to make a judgement of the relative importance of pairwise combinations of the factors involved. In making these judgments, a 9-point rating scale is used (Table 7).

The expected value method calculates the weight, W_k for criterion k depending on the number of criteria, n (Eq. 2; Janssen and Van Herwijnen, 1994).

$$W_k^{''}ev'' = \sum_{i=1}^{n+1-k} \frac{1}{n(n+1-i)} \tag{2}$$

This method takes uncertainty into account by considering the probability of each possible outcome and using this information to calculate an expected value. The rank sum method calculates the weight, W_k, for criterion k according to the following equation.

$$W_k^{rs} = \frac{n+1-k}{\sum_{i=1}^{n}(n+1-i)} \tag{3}$$

The accuracy of pairwise comparison is assessed through the computation of the consistency index (*CI*), which is a measure of departure from consistency based on the comparison matrices. The CI determines the inconsistencies in the pairwise judgments, and therefore allows for re-evaluation of comparisons. The CI is given as:

$$\mathrm{CI} = \frac{\lambda - n}{n-1} \tag{4}$$

Where, λ is the mean value of the consistency vector and n is the number of columns in the matrix (Garfi et al. 2009; Saaty 1990; Vahidnia et al. 2008). The consistency ratio (CR) is then calculated as:

$$\mathrm{CR} = \mathrm{CI}/\mathrm{RI} \tag{5}$$

Where, RI is a random index which depends on the number of elements being compared (Garfi et al. 2009). The random indexes of matrices of order 1-15 as derived by Saaty (1980) are presented in Table 8.

Table 8 Random indices (RI) for n = 1, 2. 15 (Saaty, 1980)

n	RI	n	RI	n	RI
1	0	6	1.24	11	1.51
2	0	7	1.32	12	1.48
3	0.58	8	1.41	13	1.56
4	0.9	9	1.45	14	1.57
5	1.01	10	1.49	15	1.59

Table 9 Pairwise comparison matrix for RWH areas

	Texture	Land cover	Slope	Rainfall surplus	Runoff
Texture	1	6	5	3	1
Land cover	1/6	1	1/2	1/4	1/7
Slope	1/5	2	1	1/3	1/4
Rainfall surplus	1/3	4	3	1	1/2
Runoff	1	7	4	3	1

The pairwise rating procedure has several advantages. First, the ratings are independent of any specific measurement scale. Second, the procedure, by its very nature, encourages discussion, leading to a consensus on the weights to be used. In addition, criteria that were omitted from initial deliberations are quickly uncovered through the discussions that accompany this procedure. Experience has shown, however, that while it is not difficult to come up with a set of ratings by this means, the ratings are not always consistent. Thus, the technique of developing weights from these ratings also needs to be sensitive to these problems of inconsistency and error. To provide a systematic procedure for comparison, a pairwise comparison matrix is created by setting out one row and one column for each factor in the problem (Table 9). The rating is then done for each cell in the matrix. Since the matrix is symmetrical, ratings are provided for one-half of the matrix and then inferred for the other half.

The consistency ratio (CR) of the matrix, indicative of the level of consistency achieved compared to that of a randomly-generated matrix, was 0.02, and therefore inferior to 0.10 (Saaty 1977), the rating were deemed to have an acceptable consistency

Development of a GIS-based suitability model

All the processing involved in generating a RWH suitability map was implemented in a suitability model developed in the model builder of ArcGIS 10.1. The suitability model generates suitability maps for RWH by integrating different input criteria maps using a Weighted Overlay Process (WOP), using both vector and raster databases. With a weighted linear combination, criteria were combined by applying a weight to each factor, followed by a summation of the results to yield a suitability map. This was undertaken using the weight module of Idrisi software used for this calculation. The final weight is presented in Table 10.

Suitability maps for RWH

Identifying suitable RWH sites implemented in the ArcGIS model environment was done using the model builder of ArcGIS 10.1. Based on an AHP analysis taking into account five layers, the spatial extents of RWH suitability areas were identified using MCE. Different spatial analysis tools were used in the model to solve spatial problems in the process of identifying suitable areas. The identification process in this study was considered as a multi-objective and multi-criteria problem.

The suitability model generated a suitability map for RWH with five suitability classes, i.e. excellent, good, moderate, poor and unsuitable. The spatial distribution of the suitability map (Figure 8) showed that ‘excellent’ suitable areas for RWH were concentrated in the northern part of Egypt. According to their means (Table 11), 4.8% (47910 km^2) and 14% (139739 km^2) of the study area was classified as excellent and good for RWH, respectively, while 30.1% (300439 km^2), 47.6% (474116 km^2) and 3.5% (34935 km^2) of the area were classified as moderate, unsuitable and poor, respectively.

The majority of the areas with excellent suitability had slopes between 2 and 8% and were in intensively cultivated areas. The major soil type in the excellent suitable area was loam and the rainfall ranged from 100 to 200 mm.

Table 10 Weight (percent of influence)

No.	Criteria	Weight	Weight %
1	Soil texture	0.361	36.063
2	Land cover/use	0.047	4.683
3	Slope	0.077	7.676
4	Rainfall surplus	0.160	15.996
5	Potential RC	0.356	35.582
	Sum	1	100

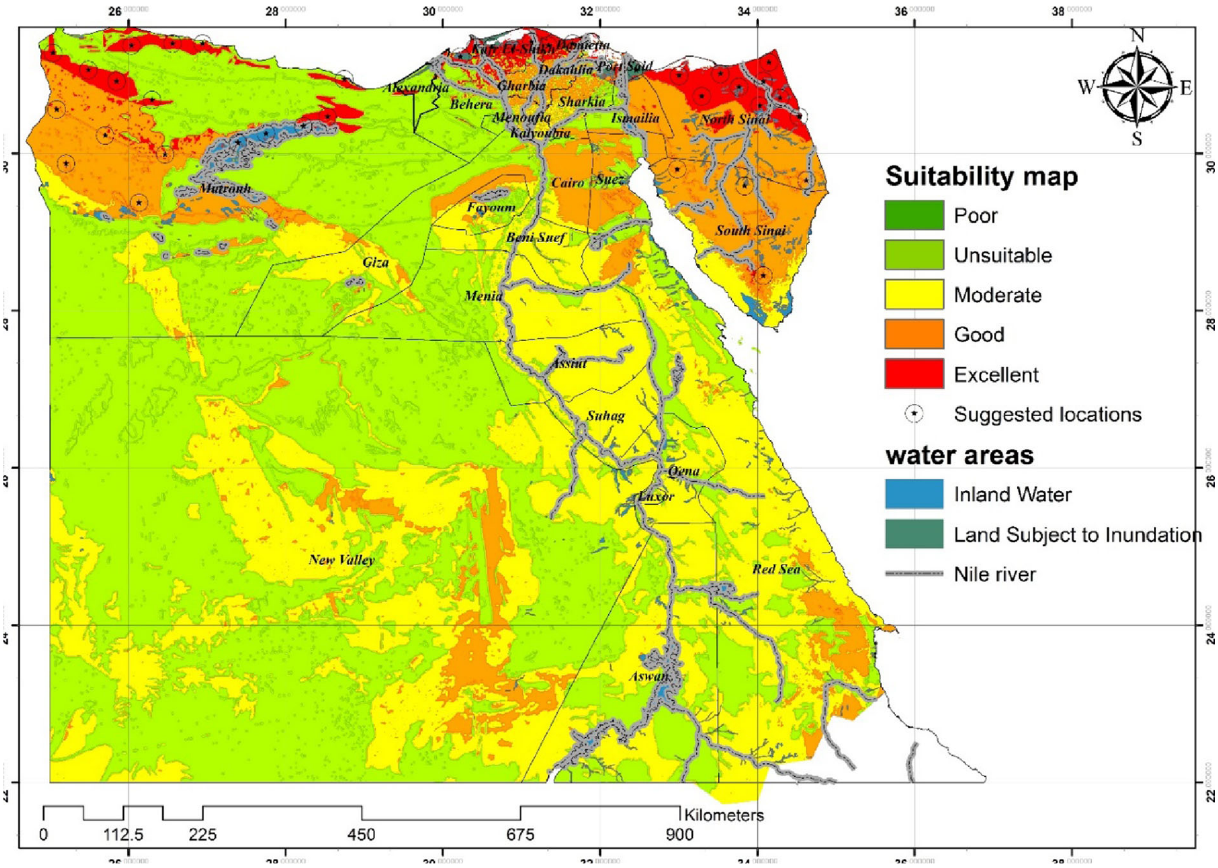

Fig. 8 suitability RWH map for the study area

The most suitable locations for rainwater harvesting in Egypt governorates lie mainly in South Sinai, North Sinai, Damietta, Ismailia, Gharbia, Matrouh, Port Said, and Kafr El-Sheikh (Table 11).

Validation of the technique employed depends on comparing existing RWH structure locations with the suitability map generated using the proximity analysis tools of ArcGIS 10.1. Most existing RWH structures were categorized as successful, as they were located in 'excellent' suitable areas. These validation results showed the database and methodology used for developing the suitability model, including the suitability levels of the criteria and the criteria's relative importance weights, to have yielded accurate results.

The outcomes of this work could be applied to help develop more integrated and adaptive water resources management (Inam et al. 2015; Butler and Adamowski, 2015) programs in Egypt by setting up RWH systems in the most suitable locations to ensure the sustainable use of scarce water resources.

Conclusion and recommendations

In the present study, suitable areas for sustainable water harvesting and storage in Egypt were identified using using remote sensing for land cover data - location assessment linked to a decision support system (DSS). The spatial distribution of the suitability map showed that the 'excellent' suitability areas for RWH were concentrated in the northern part of Egypt. On average, 3.24% of the nation's total area was found to have an 'excellent' or 'good' suitability for RWH.

This research is valuable because it can help enhance water availability and land productivity in the severely arid regions of Egypt. Nevertheless, there is a need to improve the performance of agricultural systems through ongoing efforts to develop and apply new technologies and adapt them to achieve self-sufficiency, while taking into account an assessment of the suitability of these techniques to sustain the nation's environment.

Table 11 Areas under different suitability classes

	Suitability	Area (km^2)	% of total area
Egypt	Poor	34,935	3.5
	Unsuitable	474,116	47.6
	Moderate	300,439	30.1
	Good	139,739	14
	Excellent	47,910.0	4.8
Beheira governorate	Poor	5065	50
	Unsuitable	1560	15.4
	Moderate	1185.2	11.7
	Good	1215.6	12.0
	Excellent	1104.2	10.9
South Sinai Governorate	Poor	170.6	0.6
	Unsuitable	656.3	0.3
	Moderate	119,439.6	21.0
	Good	904,328.4	63.6
	Excellent	11,781.5	14.5
Kafr el-Sheikh Governorate	Poor	487.2	13
	Unsuitable	187.4	5
	Moderate	75	2
	Good	1311.8	35
	Excellent	1686.6	45
North Sinai Governorate	Poor	1019.9	3.7
	Unsuitable	3335.2	12.1
	Moderate	1157.7	4.2
	Good	12,403.8	45
	Excellent	9647.4	35
Ismailia Governorate	Poor	20.3	0.4
	Unsuitable	1165.2	23.0
	Moderate	759.9	15.0
	Good	1094.3	21.6
	Excellent	2026.4	40
Matrouh Governorate	Poor	22,486	13.5
	Unsuitable	13,325	8.0
	Moderate	56,631.4	34
	Good	61,628.3	37
	Excellent	12,492.2	7.5

The implementation of rainwater harvesting techniques can help instigate a general awareness of water conservation among stakeholders in remote areas that suffer from a scarcity of water resources. In turn, this can help create local innovations and strategies for rainwater harvesting through ‘change agents’ (e.g. Straith et al. 2014). This study has the potential to help planners manage rainwater in similar arid regions elsewhere. Furthermore, a feasibility study can be conducted for various techniques used in harvesting rainwater to identify site-specific mechanisms that augment groundwater recharge from catchment areas, such as the construction of small dams, bounds, soil pits, recharge wells, tanks, etc. The capture of rainwater runoff may thereby increase water availability and reduce water demand.

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