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# Rainwater harvesting and storage in Asir, Kingdom of Saudi Arabia, using spatial modeling and geographic information systems

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**ABSTRACT**

This article focuses on selecting and determining optimum sites for indigenous rainwater harvesting (RWH) in the Asir region in the Kingdom of Saudi Arabia. The three biophysical factors chosen are slope percentage, rainfall, and soil texture. In addition to seven socio-economic constraints, various other parameters included in the analysis are the distance to the drainage network, road networks, international borders, urban areas, vegetated area, established dams, and faults. The different geospatial layers were then reclassified and transferred to a suitability coding number to produce the suitability map of RWH using multi-criteria analysis in combination with a geographic information system, and data from remote sensing. Overlay analysis and buffering zone applied for each socio-economic parameter. The results determined the optimal spatial sites for RWH storage within the Asir region; these findings showed that there is a sufficient area with a high potential of RWH. Thus ca. 14,261.76 km², 18.5%, of the study area, has a high or very high suitability for the RWH systems, while 9,626.99 km², 12.5% of the total area, is unsuitable. The fieldworks were carried out on the selected optimum sites for further investigation to make sure that the selected sites are not in conflict with other land use/land cover in the area.

*Keywords:* Hyper-arid land; Site selection; Land use/land cover; Water resources; Asir region, Saudi Arabia

## 1. Introduction

In the last few decades, most of the irrigated areas in arid and semi-arid regions of the world (ASARs) faced scarcity of water resources [1]. The Kingdom of Saudi Arabia (KSA) is dominated by a hyper-arid climate, with a total area of 2,150,000 km²; it occupies some 80% of the Arabian Peninsula [2]. The total cultivated area in the KSA is less than 3% of the total area, where the agricultural use is almost totally dependent on groundwater as the main source of irrigation. This resource is not only costly but is being depleted [3,4]. In addition, the domestic water use depends on the desalinated sector, which is highly costly [5,6]. Given such limitations in water resources, an increase in the potential cultivated area and the rapid population growth [4,6], rain-water harvesting (RWH) is the ideal solution to reduce the water scarcity resources in KSA, as in many of the ASARs elsewhere [1,4,5,7–11]. The main focus of this paper is on locating the optimum sites selection for RWH in the Asir region (Fig. 1), which has exceptional climatic conditions in terms of the KSA. The selection of the best sites for RWH must be based on certain criteria that take into consideration the biophysical characteristics and the socio-economic factors within the study area according to the Food and Agriculture Organization of the UN (FAO) [12]. This is integrated with geographic information system (GIS) and remote sensing (RS) applied to determine the suitable sites for RWH, based on a range of biophysical and socio-economic parameters. Many studies around

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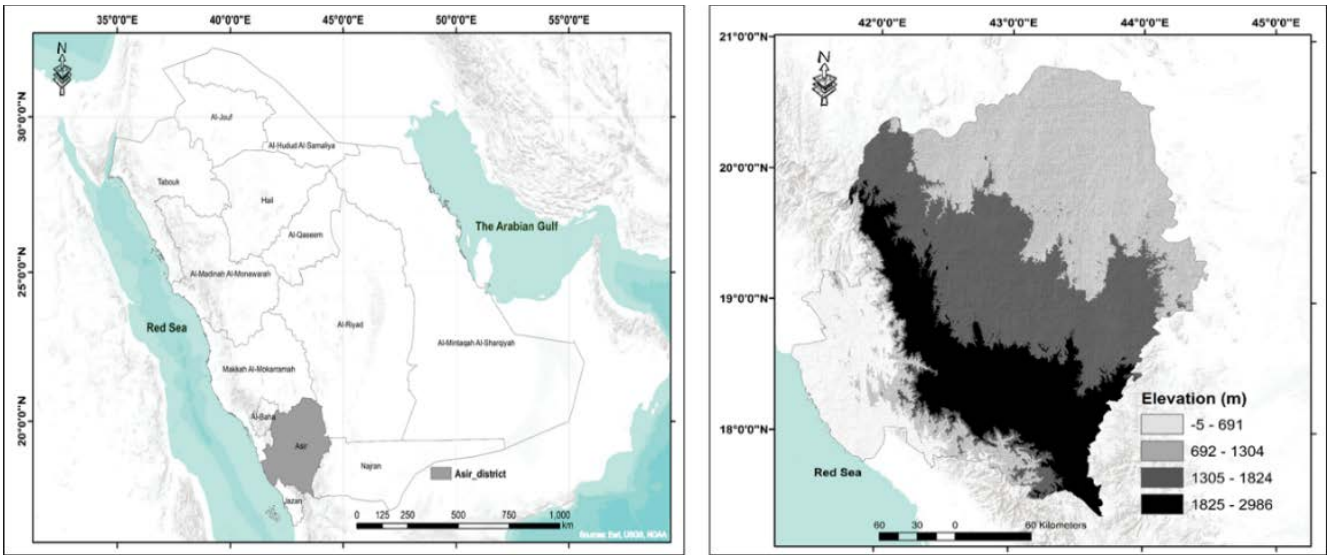


Fig. 1. The location of the study area, and a digital elevation model (DEM) of the Asir region.

the world looking at conditions in ASARs have been used analyzing socio-economic parameters combined with the main biophysical criteria, as summarized by [13]; two groupings or categories of biophysical and socio-economic criteria were used in various research studies conducted in ASARs. The first category focused only on biophysical criteria, e.g., rainfall, drainage system, slope, and use/land cover (LULC), and soil type [14–18]. The second group of studies took into account both the biophysical and socio-economic parameters, such as distance, urban, vegetated area, established dams, faults, drainage network, international borders, and road networks, population density, etc. [19–23]. Various methodologies for RWH have been adopted and applied in research [14,18]. Multi-criteria analysis (MCA) integrated with GIS and RS is utilized in many articles [19–22]. In this paper, MCA is combined with GIS tools and RS data applied to prepare input, processes, and output data for modeling of RWH, using spatial analyst tools in ArcGIS.10.6.2, GIS to determine the optimal sites for RWH, based on 10 biophysical and socio-economic factors: e.g., slope percentage, rainfall, and soil type, distance to drainage network, roads network, international borders, urban areas, vegetated area, established dams, and faults. The three biophysical factors are reclassified and overlaid to generate a site suitability map of RWH. With regard to socio-economic parameters, the buffering zones were applied for each socio-economic criterion, where the variables are classified either as true or false based on the appropriate distance listed in Table 1. The methodology of analyzing the data is summarized in Fig. 2.

## 2. Description of the study area

The KSA is dominated by a hyper-arid zone and water resources are extremely scarce, averaging less than 50 mm/y due to the low rainfall and high rate of evaporation [2]. The rainfall is characterized by extreme spatial and temporal variation [23,24]. The KSA extends between N °16.′5–°32.′5 and°33.′75–°55.′25 E. The southwestern region of the KSA is exceptional in terms of its climatic conditions. That is particularly true in the Asir region (study area here), which is located in the southwest of the KSA, it extends within a semi-arid land area

Table 1
Statistical data of the spatial distribution of the five parameters and their corresponding areas and percentages

| Elevation (m) | Area (km$^2$) | Area (%) |
|---|---|---|
| –5 – 691 | 9,366.67 | 12.16 |
| 691 – 1,304 | 38,068.17 | 49.44 |
| 1,304 – 1,829 | 25,827.83 | 33.54 |
| 1,829 – 2,906 | 3,743.13 | 4.86 |
| Slope | Area (km$^2$) | Area (%) |
| >10 | 2,354.1 | 3.06 |
| 5–10 | 16,155.38 | 20.98 |
| 5–3 | 6,008.09 | 7.8 |
| <3 | 52,489.34 | 68.16 |
| Rainfall | Area (km$^2$) | Area (%) |
| <100 | 25,620.05 | 33.27 |
| 100–150 | 20,931.97 | 27.18 |
| 150–200 | 25,899.04 | 33.63 |
| >200 | 4,555.25 | 5.92 |
| LULC | Area (km$^2$) | Area (%) |
| Agricultural area | 9,016.17 | 11.71 |
| Built up area | 755.08 | 0.98 |
| Bare area | 35,298.23 | 45.84 |
| Pasture area | 31,936.90 | 41.47 |
| Soil texture | Area km$^2$ | Area (%) |
| Sandy | 1,460.54 | 1.90 |
| Gravelly | 53,975.33 | 70.09 |
| Gravelly loam | 16,697.93 | 21.68 |
| Loamy | 4,872.98 | 6.33 |
| Sum Area km$^2$ | 77,006.78 | 100 |

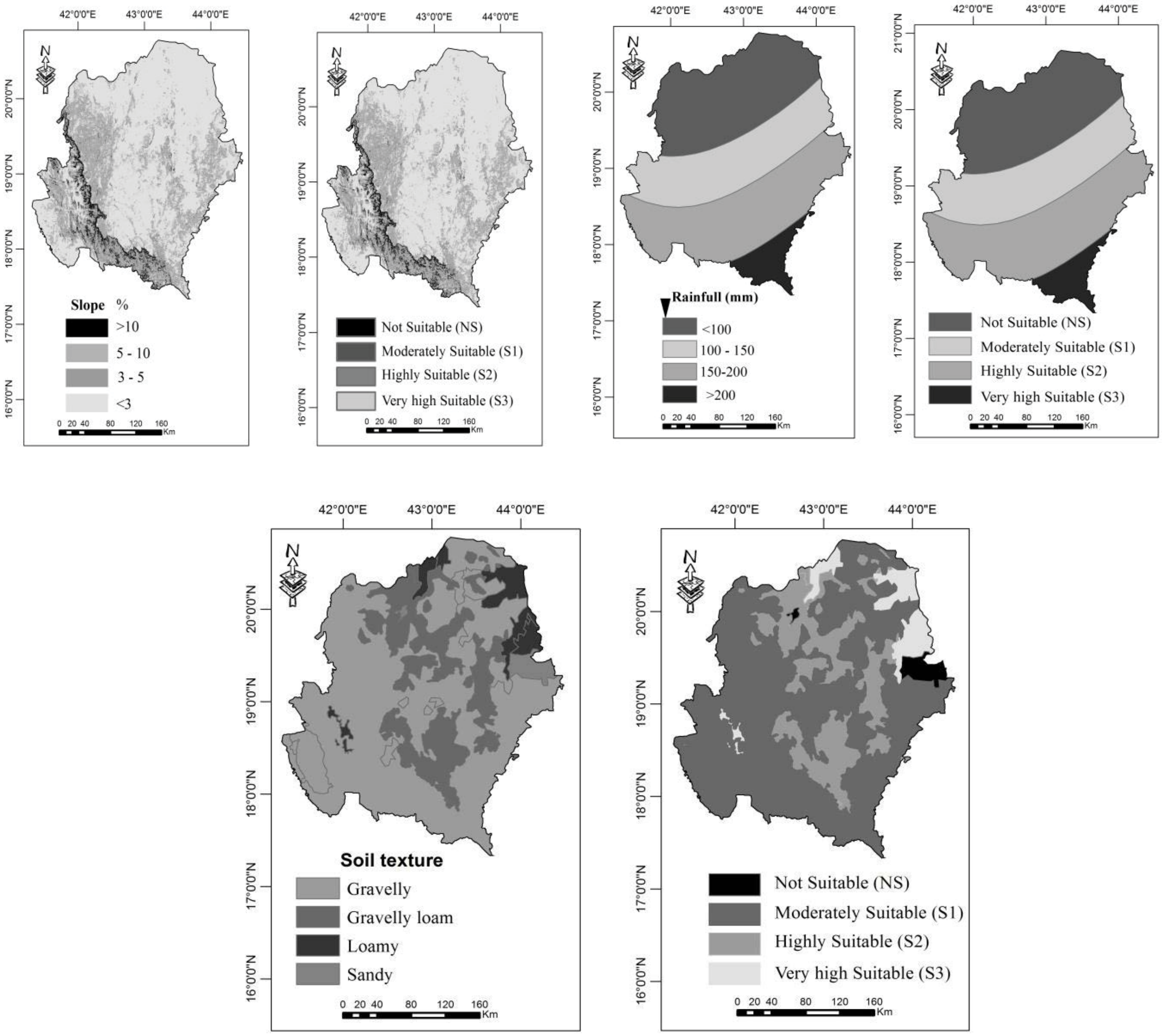


Fig. 2. The result of MCA analysis of slope percentage, mean annual rainfall, and soil texture, respectively.

at°17′72–°21′54 N and °43 ′3°44 ′52 E (Fig. 1). With a total area of 77,006, 86 $km^{2,}$ it forms about 3.5% of the total area of the KSA, with an estimated population of 2,211,875 [25]. Ground elevation ranges between −5 m below the mean sea level (B.M.S.L) at the Red Sea shoreline to 2,986 m above the mean sea level (A.M.S.L) near the Yemeni border at Sawda Mount, which is the highest elevation in the KSA. Asir is considered an exceptional region in terms of its climate as well as its topographic heterogeneity (Fig. 1). Asir is marked by the highest rainfall in the KSA in the southwestern mountainous zone, with significant variations according to altitudes. Thus, the annual mean of rainfall reaches 500 mL in the higher areas and falls to less than 100 mm in the hilly and coastal plain areas. The rainfall comes in two rainy seasons, the main one being in March and April, with some rain in the summer because Asir is influenced by the Indian Ocean monsoons, resulting in 60% of the total surface water of the Kingdom, and consequently appears to offer a better potential for sustained farming [6,22]. The rainfall has high intensity, which causes flash flooding [26,27]. Approximately 11.71% of the study area is dominated by vegetation based on the results of Thematic Mapper Landsat 8-OLI (2019). With a high potential for constructing water harvesting, the total number of dams in the KSA is 210, of which 43 were established in Asir [26,28]. Irrigation has greatly expanded production in the last few decades, depending both upon precipitation and groundwater; is important to note that the groundwater is being depleted [3,29].

## 3. Data sources, management, and methodology

Since 2003, the identification of suitable sites for RWH techniques has depended on two main groups of criteria: biophysical and socio-economic factors, as recommended by the FAO [12]. In this paper, 10 factors have been selected for identifying suitable sites for RWH. The basic major criteria that determine and impact the suitability sites for RWH are rainfall, soil texture, and slope percentage [15]. In addition, other factors are the distance to the drainage network, roads network, international borders, urban areas, vegetated area, established dams, and faults. The 10 thematic layers generated from different sources, and all 10 layers are projected according to (Ain-el-abed UTM –Zone-38N), and are converted, reclassified and overlaid to site as the optimum sites for RWH, using MCA and the tools of GIS. The classification of the selected criteria is based on different studies applied in ASARs [13] and the socio-economic parameters as listed by the FAO [12]. In this study, seven socio-economic parameters were chosen. Buffering, union, and raster reclassification were applied for each socio-economic parameter based on the appropriate buffer distance according to numerous studies [29], and consequently, a summary of these parameters.

### *3.1. Aster digital elevation model*

With the horizontal resolution of 30 meters downloaded for the study area from [30]. http://asterweb.jpl.nasa.gov/. DEM, field surveying, and observations were utilized to analyze and extract the topographical characteristics, especially the elevation and slope, in addition to delineation of the watershed characteristics such as flow direction, flow accumulation and, stream order; these were computed using Arc GIS.V10.6.2 (Spatial Analyst-Surface tools). Stream order was computed according to Strahler's system of 4th stream order [31], where slope percentage and drainage networks are essential for RWH. The slope percentage dataset was divided into four different categories (Table 1).

### *3.2. Slope percentage map*

The slope percentage dataset was reclassify using Arc GIS.V10.6.2 (Spatial Analyst-Surface tools), and divided into four different categories for representing levels of slope suitability for RWH, as shown in Fig. 3 and Table 1. The ground slope is a key factor for all applications of RWH systems. Water harvesting is recommended for areas where the slope is less than 5% [12]. The average slope influences the period of the concentration and impacts directly the runoff generated by rainfall, and the spatial distribution of the runoff is characterized by extreme variation. Thus, it transports huge amounts of different earth materials, and this reduces the economic importance of RWH applications [11]. The slope of the study area (Fig. 2) is classified into four levels: nearly level 3%, gentle slope 3%–5%, moderate slope 5%–8%, and strong to ridge slope >10%.

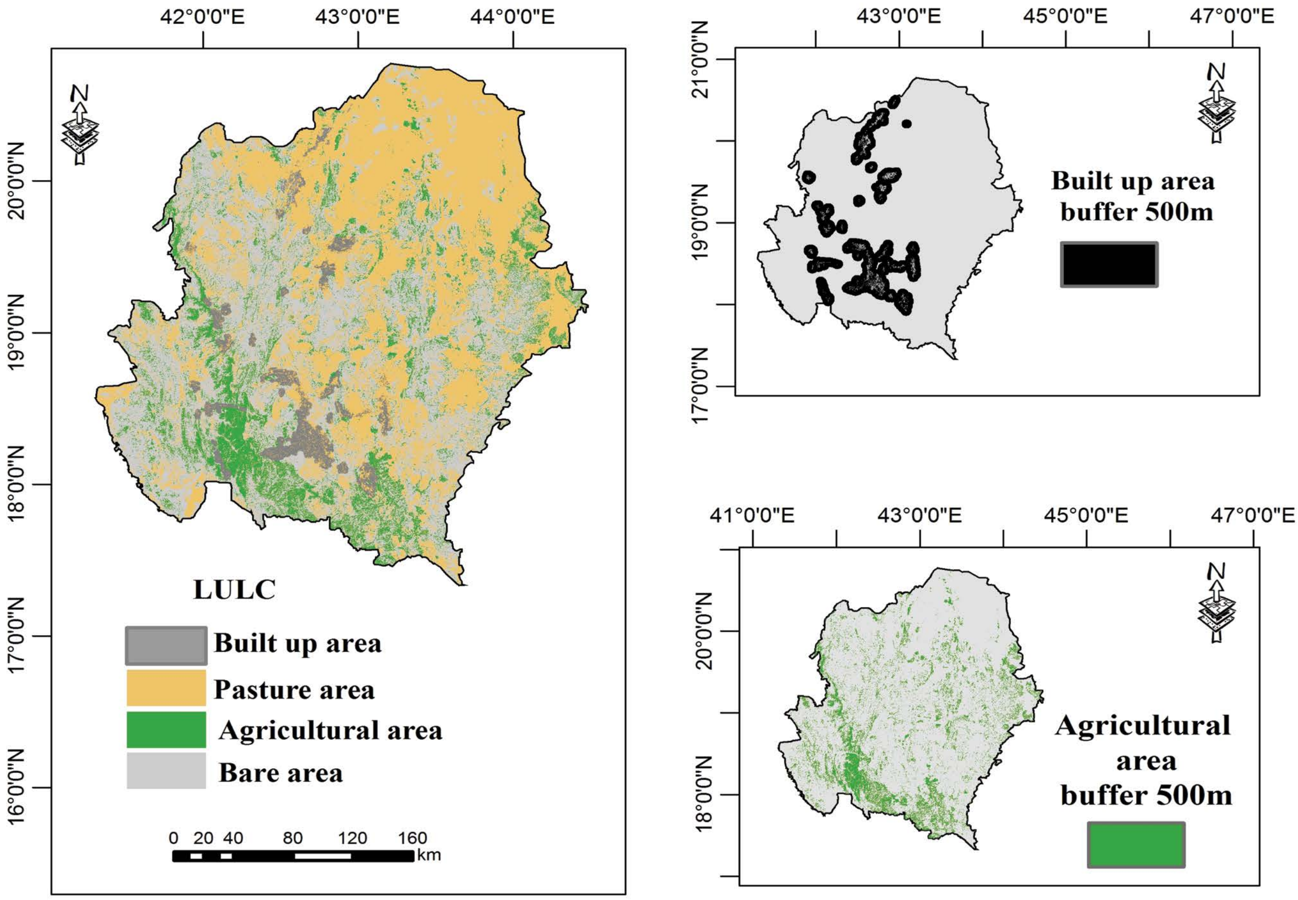


Fig. 3. LULC extracted from Landsat 8-OLI (2019), and buffering results/constraints (urban and vegetated areas analysis).

*3.3. Extraction of drainage network*

The watershed delineated was computed from the DEM using Arc GIS.V10.6.2 (spatial analyst-surface tools, hydrology). The study area has 4th stream order according to Strahler's system [31], as shown in Fig. 2. The drainage network collects runoff in the rainy season directing it towards the wadis, and this transports a huge amount of sediment, thus reducing the storage capacity of the RWH.

*3.4. Climatic data: rainfall distribution and amounts*

Rainfall is the major factor in any water harvesting system according to the FAO [12]. The mean annual rainfall data with spatial distribution and amounts were acquired from the Saudi Ministry of Agriculture and Water [32]. During the period 2000–2020, the mean annual rainfall was converted to shapefile, digitized, and interpolated by applying the spatial analyst tools to convert the rainfall data from a point map to a spatial map using ordinary kriging [33]. As a result of the topographic contrast and heterogeneity of Asir, the mean annual rainfall varies from less than <100 mm, which covered 33.27% of the total area of Asir and concentrated in the northern part, to >200 mm, representing only 5.92% of the total area of Asir and concentrated in the southern part of Asir (Fig. 2).

*3.5. Soil texture map*

Soil texture was obtained from MAW [32]; the soil map was converted to shapefile, digitized, and classified according to its texture into four classes: sandy, gravelly, gravelly loam, and loamy. These constitute 1.9%, 70.09%, 21.68%, and 6.33% respectively of the total, as shown in Fig. 3 and Table 2. Soil texture is very important for RWH. Soil with a sandy texture is not recommended for the application of water harvesting, as the infiltration rate is higher than the rainfall intensity [23]. In the Asir region, the loamy and gravelly loamy soil is highly and very highly suitable for RWH, forming 30% of the total area of Asir (Fig. 2).

Table 2
Classification of the suitability according to the three parameters used in analysis, by area and percentage

| Suitability Class | Slope area (km$^2$) | Area (%) |
|---|---|---|
| Very highly suitable – (S3) | 52,489.34 | 68.16 |
| Highly suitable – (S2) | 16,155.38 | 20.08 |
| Moderately suitable – (S2) | 6,008.09 | 7.8 |
| Not suitable – (NS) | 2,359.1 | 3.96 |
| Total area (km$^2$) | 77,006.3 | 100 |
| Suitability Class | Mean annual rainfall-area (km$^2$) | |
| Very highly suitable – (S3) | 25,620.05 | 33.27 |
| Highly suitable – (S2) | 20,931.97 | 27.8 |
| Moderately suitable – (S2) | 25,899.04 | 33.1 |
| Not suitable – (NS) | 4,555.25 | 5.92 |
| Total area (km$^2$) | 77,006.3 | 100 |
| Suitability Class | Soil area (km$^2$) | Area (%) |
| Very highly suitable – (S3) | 1,460.54 | 1.90 |
| Highly suitable – (S2) | 4,872.98 | 6.33 |
| Moderately suitable – (S2) | 53,975.33 | 70.09 |
| Not suitable – (NS) | 16,697.93 | 21.68 |

*3.6. Land use/Land cover (LULC) map*

The Thematic Mapper Landsat 8-OLI (2019) was downloaded from the USGS website [34]. It was selected for April, covering the study area for the year 2019 at a resolution of 30 m × 30 m. The visible and Near Infrared (NIR) bands were combined to create layer stacking using GIS tools. After that, the Landsat values were geometrically corrected using distinct ground features such as road crosses, and then the Landsat images were mosaicked, subset and clipped to the borders of the Asir. A supervised classification method with a maximum likelihood algorithm was applied in Arc GIS.10.6.2. Four LULC patterns are identified; these comprise: built-up area, pasture area, agricultural area, and bare area. Approx. 9,016.17 km² (11.71%) of Asir was classified as agricultural area, 755.08 km² (0.98%) comprised built-up area, 35,298.23 km² (45.84%) was classified as bare land, and 31,936.90 km (41.47%) was classified as constituting pasture area, as shown in Table 1 and Fig. 3. LULC is one of the most essential variables for RHW. The main patterns of LULC should be excluded from sites selecting which are agricultural and built-up areas. The faults, roads, the established dams and the international borders were obtained from MAW [32]. Scanning was employed: conversion into a digital format at 600 DPI jpg, georeferencing, digitizing using ArcGIS software (on-screen digitizing), and masking by the boundary of the study area as a shape file [35,36]. Then all the patterns of socio-economic layers (polygon, linear, and point) – including distance to urban areas, vegetated area, established dams, faults, drainage network, international borders, and roads network – were integrated into the result map, as shown in Fig. 3. Buffering zones are applied for each socio-economic criterion based on the appropriate buffer distance, as listed in Table 2 [18]. Then the socio-economic factors were converted to raster format and merged with the study area using the union tools, and the raster reclassification is applied for all these layers. All criteria will be given equal weights, suitable and unsuitable, and this will be used to rate all layers.

*3.7. Data processing*

The suitability maps for RWH were generated based on the three different biophysical criteria; all these criteria were reclassified into four levels as listed in Table 2. The raster dataset values 1, 2, 3, and 4 were converted into suitability codes: not suitable (S1), moderately suitable (S2), highly suitable (S3), and very highly suitable (S4). Buffer zones create each of the seven socio-economic parameters in order to exclude from suitability site selection for the RWH system. Then all socio-economic criterion patterns (polygon, lines, and points) were spatially merged with the study area using the union technique. All the seven socio-economic criteria were given equal weights, (suitable or suitable), which are used to rate all layers. Then the

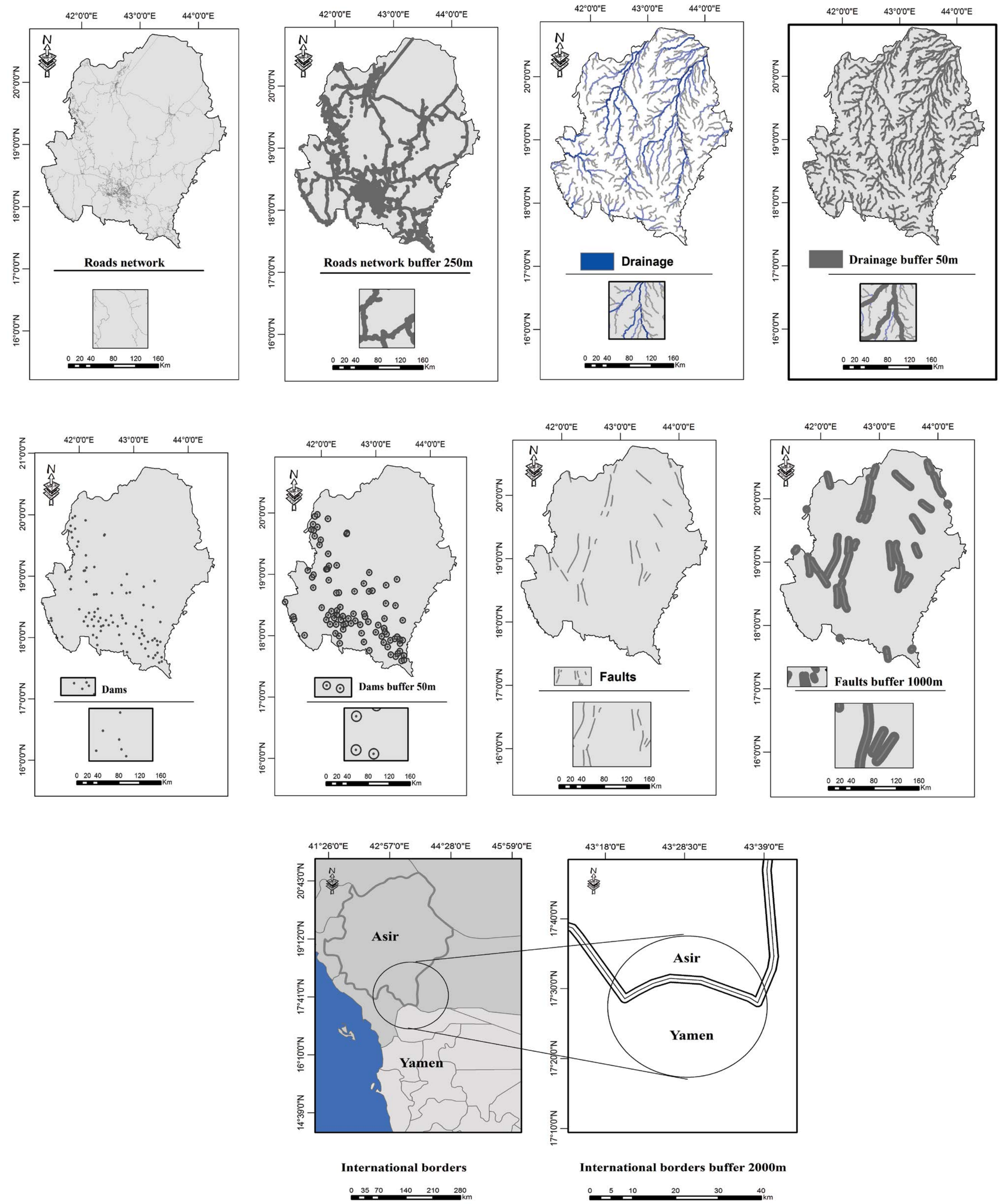


Fig. 4. The results of buffering analysis (constraints); including distance to the roads network, drainage network, established dams, faults and international borders.

raster reclassification is applied for all layers based on the values listed in Table 4. After that, the MCA tool is used to create the map with the four suitability levels for RWH, by combining the three selected biophysical criteria into one outcome. Thus, the results of the MCA and the buffering tools were integrated to generate a final suitability map for the RWH system. The schematic diagram is shown in Fig. 5.

### 3.8. MCA and buffering analysis for site selection

All 10 biophysical and socio-economic factors (constraints) were used to select the optimum sites of RWH in the Asir region. These criteria include rainfall, slope percentage, soil types, in addition to the seven socio-economic layers, e.g., distance to the drainage network, roads network, international borders, urban areas, vegetated area, established dams, and faults. The MCA suitability maps for the selected RWH systems were generated and classified into four levels of suitability: not suitable (S1), moderately suitable (S2), highly suitable (S3), and very highly suitable (S4). The results are shown in Figs. 2 and 4. Seven buffer criteria were used: e.g., distance to urban areas, vegetated area, established dams, faults, drainage network, international borders, and the roads network. Table 4 provides a brief description of these buffering criteria and the justification for choosing them within the overall site selection. The use of buffer criteria is of great importance in order to exclude unsuitable sites that have been selected by the MCA method. In the final step, the three biophysical and the constraints layers were combined, and the probable RWH sites in Asir were selected using overlay tools (map algebra toolset). The main result from the final map (Fig. 6) showed the spatial distribution of the four different suitability levels, where very highly and highly suitable sites are concentrated in southwestern Asir, with a total area of 18.5%, whereas most of the study area is classified into moderate and unsuitable zones for RWH, as shown in Fig. 6 and Table 5. These results reflect the heterogeneity of the study area, practically in terms of altitude and the patterns of landforms as shown in Fig. 1, the digital elevation model. There ca. 38.4% of the total Asir region has an elevation of more than 1,300 m, which represents the high mountainous area, and 49.4% with an elevation 691–1,304 m, representing the hilly flat area; the remainder constitutes low lands along the eastern Red Sea shoreline.

## 4. Results and discussion

In order to locate the suitability sites for RWH, an integrated system of suitability assessment was employed taking into account all 10 biophysical and socio-economic factors; this is summarized in Tables 3 and 4. These parameters include rainfall, slope percentage, soil texture, in addition to the socio-economic parameters, for example, the distance to drainage networks, the roads network, international borders, urban areas, vegetated area, established dams, and faults. The three main factors recommended for any RWH system are the slope percentage, rainfall, and soil texture. The slope is the most essential factor in any RWH systems site selection. The suitability slope analysis showed that 52,489.34 km², about 68.16% of the total area of Asir is very highly suitable, since nearly flat (0–<3%), as noted in Table 1. The sites with flat slopes were the most suitable for rainwater harvesting, while moderate slope (5%–8%), and strong slope (>10%) are not recommended for RWH [12]. Soil texture is an important factor in selecting an RWH site for different uses, according to the suitability analysis in the soil texture. Table 1 shows that

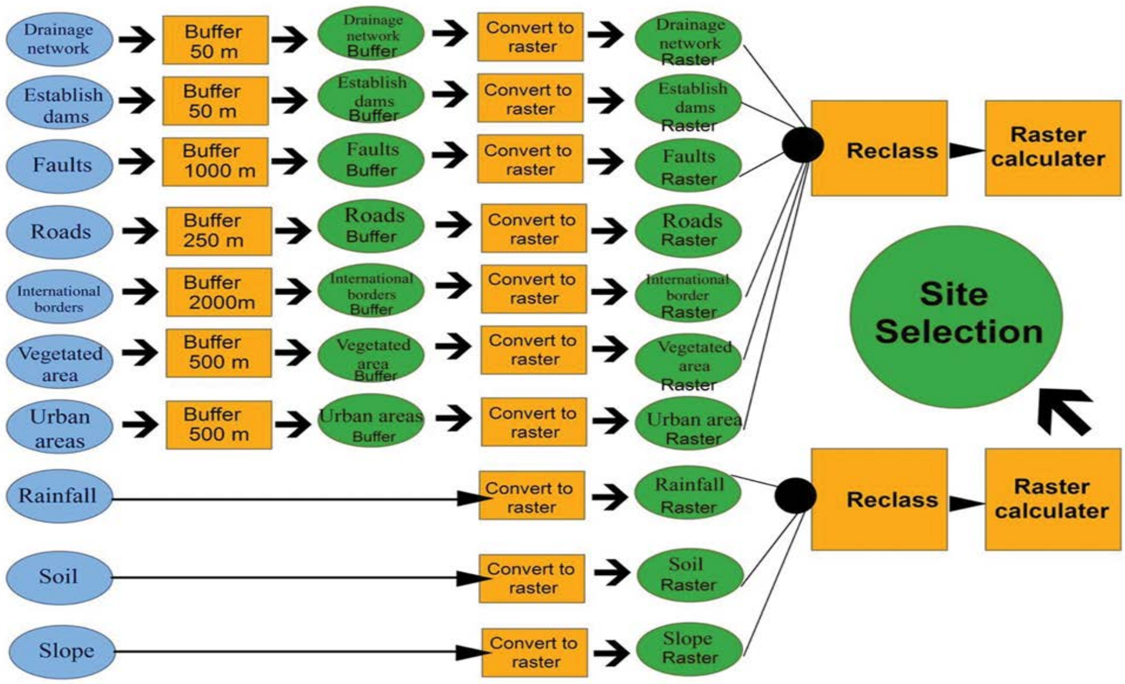


Fig. 5. Flowchart of steps and methods applied in this study.

Table 3
Different criteria preference value for RWH, according to [8,12,13,15,16]

| Suitability type | Suitability for sites selection of RWH | | | |
|---|---|---|---|---|
| Suitability class/criteria type/scores | S4 | S3 | S2 | NS (S1) |
| Slope (%) | <5 | 5–8 | 8–15 | >15 |
| Soil texture | Loamy | Gravelly loam | Gravelly | Sandy |
| Precipitation (mm) | >250 | 150–200 | 100–150 | <100 |

Table 4
Constraints factors and their justifications, based on [14–18], with minor modifications

| Number | Parameters | Ratings | Value |
|---|---|---|---|
| 1 | Distance to drainage network | >50 m | 1 |
| | | <50 m | 0 |
| 2 | Distance to roads network (m) | >250 | 1 |
| | | <250 | 0 |
| 3 | [a]Distance to international borders (m) | >2,000 | 1 |
| | | <2,000 | 0 |
| 4 | Distance to urban (m) | >500 | 1 |
| | | <500 | 0 |
| 5 | Distance to established dams (m) | >50 | 1 |
| | | <50 | 0 |
| 6 | Distance to faults (m) | >1,000 | 1 |
| | | <1,000 | 0 |
| 7 | Distance to vegetated area (m) | >500 | 1 |
| | | <500 | 0 |

The value is identified based on the circumstances predominant within the Asir region.
[a]Because of the historical conflict between Yemen and Saudi Arabia at the border, many key installations have recently been subjected to Houthi attacks during 2019/2020.

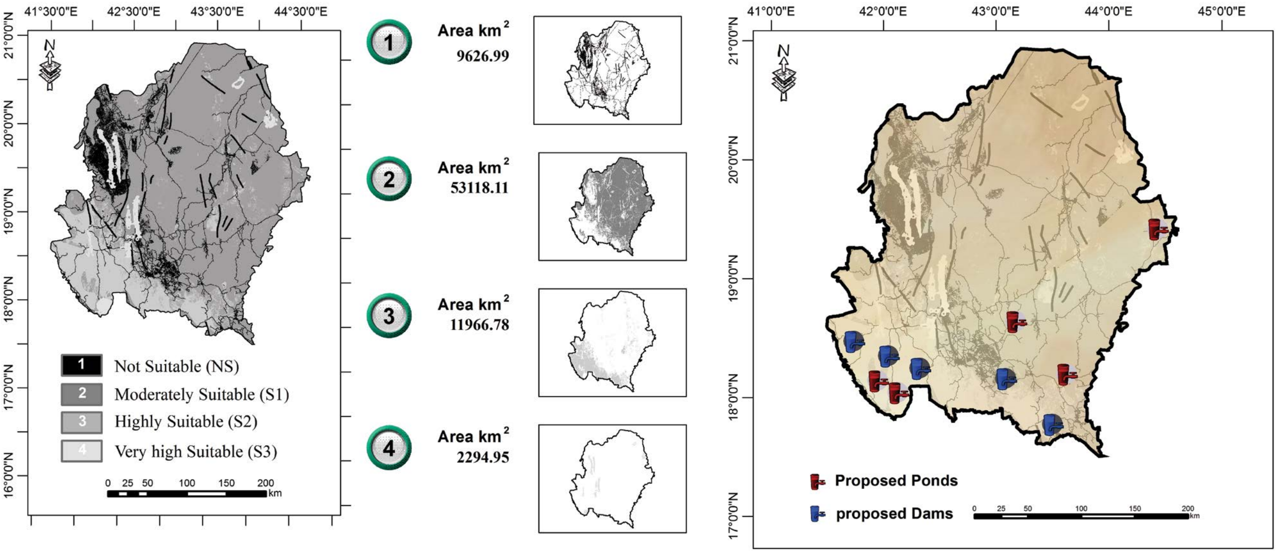


Fig. 6. The results of suitability from the 10 parameters (MCA and constraints criteria), using equal weights, and selected proposed dams and ponds for validation.

highly and very highly suitable soils represent only 7.32% of the total area of the Asir region, which is covered by loamy and gravelly loam soils. In contrast, the study area is dominated by gravel and sand soils, forming 91.7% of the total area of Asir (Fig. 2). The mean annual rainfall in the study area ranges between <100 mm distributed in the northern part to >200 mm, representing only 5.92% of the total area of Asir with spatial distribution in the southern part of Asir. In spite of that, there are no perennial rivers in the Asir region; there are dense drainage networks and the runoff is concentrated in wadis, causing flash floods [37]. The southwestern part of the study area is identified as the most suitable zone for water harvesting, as it has been shown that these areas have the maximum average rainfall (>200 mm), with slopes of less than 3%. The distance to road network expansion should be considered in the planning of RWH projects. The distance between RWH structures and roads is to avoid any future conflict between the construction of RWH patterns and roads development. The distance to faults represents a major obstacle when deciding to have a water harvesting system, and it is important to exclude the fault area from the selected sites [15,17]. The distance to international borders >2,000 m is a factor, because of the historical conflict between Yemen-Saudi Arabia along the borders, and recently many key installations have been subjected to Houthi attacks. Urban and agricultural areas must be excluded from being selected as water harvesting sites for safety and other reasons [15]. As a result, Fig. 6 indicates that highly and very highly suitable sites for RWH were concentrated in the southwestern part of the study area, 11,966.78 km² (ca. 15.5%) and 2,294.98 km² (ca. 3%) of the study area resp. These areas have a high mean level of rainfall (Fig. 2). By contrast, 9,626.99 km² (12.5%) of the total area was classified as unsuitable and most of the study area is classified as moderately suitable 53,118.11 km² (69%) of the total area of Asir. The northern part of the study area is a hilly complex in its topography compared to the southern section, with its rainfall (<100 mm), and rainfall is considered to be the most important single factor in RWH. In the south zone of the study area, generally, all seven socio-economic parameters are considered unsuitable for RWH and constitute a space occupying 12.6% of the study area.

Table 5
Area (km²) and percentage (%) for each suitability level

| Suitability Levels | Area (km²) | Area (%) |
|---|---|---|
| Not suitable – (NS) (S1) | 9,626.99 | 12.5 |
| Moderately suitable – (S2) | 53,118.11 | 69 |
| Highly suitable – (S3) | 11,966.78 | 15.5 |
| Very highly suitable – (S4) | 2,294.98 | 3 |
| Total | 77,006.86 | 100 |

### 4.1. Validation

It is necessary to verify the accuracy of the study results with regard to determining suitable areas for RWH based on the 10 factors that were employed and applied in this study. The fieldworks must be carried out on the selected sites for further investigation to make sure that the selected sites are not in conflict with other LULC in the area which are not shown to the researcher through the available RS data and GIS analysis results. To achieve this goal, 10 proposed sites for dams and ponds (the most common for RWH in the study area) were proposed randomly in the most suitable area for RWH, as shown in Fig. 6. According to the fieldwork and the requirements for determining the best sites for RWH, these proposed sites can achieve the theoretical requirements of RWH that were applied in this paper, as shown in Table 6.

## 5. Conclusions and recommendations

Since the main objective of this paper is to identify the most suitable sites for RWH in a semi-arid region with high-intensity rainfall causing flash floods on rainy days. In addition, the study area is characterized as

Table 6
Characteristics of the proposed sites

| Dams N. | *X* | *Y* | Slope (%) | Rainfall (mm) | Elevation (m) | Soil texture | LULC patterns |
|---|---|---|---|---|---|---|---|
| 1 | 427,461.0783 | 2,126,971.156 | <3 | 150–200 | 150 | Loamy | Bare land |
| 2 | 291,102.2726 | 2,050,442.478 | <3 | 150–200 | 320 | Loamy | Bare land |
| 3 | 159,860.0886 | 2,003,968.855 | <3 | 150–200 | 257 | Loamy | Bare land |
| 4 | 177,731.5394 | 1,991,661.694 | <3 | 150–200 | 750 | Loamy | Bare land |
| 5 | 334,509.4469 | 1,998,545.622 | <3 | >200 | 600 | Loamy | Bare land |
| Ponds N. | *X* | *Y* | Slope (%) | Rainfall (mm) | Elevation (m) | Soil texture | LULC patterns |
| 6 | 140,137.8155 | 2,042,018.725 | <3 | 150–200 | 789 | Loamy | Bare land |
| 7 | 318,728.8628 | 1,952,936.578 | <3 | >200 | 1200 | Gravelly loam | Bare land |
| 8 | 171,380.3345 | 2,026,269.835 | 3–5 | 150–200 | 165 | Loamy | Bare land |
| 9 | 199,647.1515 | 2,012,857.814 | <3 | 150–200 | 400 | Loamy | Bare land |
| 10 | 278,375.8994 | 1,998,019.564 | <3 | 150–200 | 250 | Loamy | Bare land |

heterogeneous topography. The identification of suitable sites for RWH systems was based on two sets of criteria: three biophysical factors and seven socio-economic factors, using MCA integrated with GIS tools. The biophysical factors were reclassified into four RWH suitability levels: for example, very highly suitable, highly suitable, moderate suitable, and unsuitable. On the other hand, a buffer zone was used to exclude unsuitable sites for RWH systems based on socio-economic factors, and results of the buffering method were classified into two levels, suitable and unsuitable. Then, the MCA and the buffering method were combined to create a final suitability map for the RWH system. The final suitability map was classified into four levels as shown in Fig. 6 and Table 5. The results showed that the southwestern region of the study area is the most suitable for RWH. Specifically for, dams and Al-Hafira (ponds). The northern region of the study area included mostly hilly and mountainous areas, in comparison with the southern part, which has plains with gentle to moderate slopes. The results showed that very highly suitable sites covered 3% of the total study area, while highly suitable sites covered 15.5%. By contrast, 12.5% of the total area of Asir is unsuitable, and most of the Asir region is classified as moderately suitable, covering 69% of the total study area, with space distributed in the central and northern part of the study area. The study recommended that RS data and GIS tools could be used in arid and semi-arid regions around the world to select the optimum sites for water harvesting. In addition, the methodology adopted in this article can be more accurate through historical data for rainfall and temperature. Besides the suitability map, 10 possible dams and ponds sites were proposed and validated according to fieldwork as shown in Fig. 6.

Furthermore, the study recommended that fieldworks must be carried out on the selected sites for further investigation to make sure that the selected sites are not in conflict with other LULC in the area, which are not identified to the researcher through the available RS data and GIS analyses.

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## References

[1] O.A. Isioye, M.W. Shebe, UI.O. Momoh, C.N. Bako, A Multicriteria Decision Support System (MDSS) for identifying rain water harvesting site (s) in Zaria, Kaduna State, Nigeria, Int. J. Adv. Sci. Eng. Technol. Res., 1 (2012) 53–71.

[2] P. Meigs, World Distribution of Arid and Semi-Arid Homoclimates, In Reviews of Research on Arid Zone Hydrology, Paris, United Nations Educational, Scientific, and Cultural Organization, Arid ZoneProgramme-1, 1953, pp. 203–209.

[3] Z. Şen, K. Al-Suba, Hydrological considerations for dam siting in arid regions: a Saudi Arabian study, Hydrol. Sci. J./Journal des Sciences Hydrologiques, 47 (2002) 173–186.

[4] S. Chowdhury, M. Al-Zahrani, Characterizing water resources and trends of sector wise water consumptions in Saudi Arabia, J. King Saud Univ. Eng. Sci., 27 (2015) 68–82.

[5] K.H. Al-Zahrani, Water demand management in the Kingdom of Saudi Arabia, Conf. Int. J. Art. Sci., 2 (2010) 68–76.

[6] M. Elhag, Detection of temporal changes of Eastern Coast of Saudi Arabia for better natural resources management, Indian J. Geomar. Sci., 45 (2016) 29–37.

[7] MAW (Ministry of Agriculture and Water), Agricultural Statistical Year Book 7, Ministry of Agriculture and Water, Riyadh, Department of Economic Studies and Statistics, 1992.

[8] K.S. Balkhair, Outranking Strategic Groundwater Basins in Western Saudi Arabia Using Multi-criterion Decision Making Techniques, Sherif, Sing, Al-Rashed, Eds., Groundwater Hydrology, Swets and Zeitlinger, Lisse, 2002, pp. 325–342.

[9] S.H. Mahmoud, A.A. Alazba, The potential of in situ rainwater harvesting in arid regions: developing a methodology to identify suitable areas using GIS-based decision support system, Arabian J. Geosci., 8 (2014) 5167–5179.

[10] H. Weerasinghe, U.A. Schneider, A. Löw, Water harvest- and storage-location assessment model using GIS and remote sensing, Hydrol. Earth Syst. Sci. Discuss., 8 (2011) 3353–3381.

[11] M. Elhag, J. Bahrawi, Potential rainwater harvesting improvement using advanced remote sensing applications, Sci. World J., 2014 (2014) 806959, doi: 10.1155/2014/806959.

[12] FAO, Land and Water Digital Media Series, 26. Training Course on RWH (CDROM), Planning of Water Harvesting Schemes, Unit 22, Food and Agriculture Organization of the United Nations, FAO, Rome, 2003.

[13] A. Ammar, M. Riksen, M. Ouessar, C. Ritsema, Identification of suitable sites for rainwater harvesting structures in arid and semi-arid regions: a review, Int. Soil Water Conserv. Res., 4 (2016) 108–120, doi:10.1016/j.iswcr.03.001.

[14] J.M. Kahinda, E. Lillie, A. Taigbenu, M. Taute, R. Boroto, Developing suitability maps for rainwater harvesting in South Africa, Phys. Chem. Earth, 33 (2008) 788–799.

[15] R. Al-Adamat, A. Diabat, G. Shatnawi, Combining GIS with multicriteria decision making for siting water harvesting ponds in Northern Jordan, J. Arid. Environ., 74 (2010) 1471–1477.

[16] R. Al-Adamat, GIS as a decision support system for siting water harvesting ponds in the basalt aquifer/NE Jordan, J. Environ. Assess. Policy Manage., 10 (2008) 189–206, doi: 10.1142/S1464333208003020.

[17] G. Shatnawi, Determine the Best Sites for Water Harvesting Projects (Dams & Hafirs) in Northeastern Badia using GIS Applications, Unpublished M.Sc. Thesis, Al Al-Bayt University, Jordan, 2006.

[18] R. Al-Adamat, S. Al-Ayyash, H. Al-Amoush, O. Al-Meshan, Z. Rawajfih, A. Shdeifat, M. Al-Farajat, The combination of indigenous knowledge and geo-informatics for water harvesting siting in the Jordanian Badia, J. Geogr. Inf. Syst., 4 (2012) 366–376.

[19] M.G. Kumar, A.K. Agarwal, R. Bali, Delineation of potential sites for water harvesting structures using remote sensing and GIS, J. Indian Soc. Remote Sens., 36 (2008) 323–334.

[20] S.M.J. Baban, K. Wan-yusof, Modelling optimum sites for locating reservoirs in tropical environments, Water Resour. Manage., 17 (2003) 1–17.

[21] L. K. Singh, M. K. Jha, V.M. Chowdary, "Multi-criteria analysis and GIS modeling for identifying prospective water harvesting and artificial recharge sites for sustainable water supply, J. Cleaner Prod., 142 (2017) 1436–1456, doi: 10.1016/j.jclepro.2016.11.163.

[22] J.R. Eastman, H. Jiang, J. Toledano, Multi-criteria and Multi-objective Decision Making for Land Allocation Using GIS, Multicriteria Analysis for Land-Use Management, Springer, Berlin/Heidelberg, 1998, pp. 227–251.

[23] A. Adham, M. Riksen, M. Ouessar, C. Ritsema, Identification of suitable sites for rainwater harvesting structures in arid and semi-arid regions: a review, Int. Soil Water Conserv. Res., 4 (2016) 108–120.

[24] W.A. Abderrahman, Water Demand Management in Saudi Arabia, N.I. Farukui, A.K. Biswas, M.J. Bino, Eds., Water

Management in Islam, The International Development Research Centre (IDRC), 2000, pp. 68–78.
[25] General Authority of Statistics of KSA, 2017. Available at: https://www.stats.gov.sa/en
[26] M. Al-Jerash, Models of estimating average annual rainfall over the west of Saudi Arabia, J. Fac. Arts Humanit., 3 (1983) 107–152, King Abdulaziz University, Jeddah, Saudi Arabia.
[27] M. Nouh, Analysis of rainfall in southwest region of Saudi Arabia, Proe. Insln Civil Eng., 83 (1987) 339–349.
[28] M. Al-Jerash, Climatic water balance in Saudi Arabia: an application of Thornthwaite-Mather model, J. Fac. Arts Hunanit., 5 (1988) 1–62.
[29] D. Yi Yang, Application of GIS and remote sensing for assessing watershed ponds for aquaculture development in Thai Nguyen, Vietnam, 2003. Available at: http://www.gisdevelopment.net
[30] http://asterweb.jpl.nasa.gov/
[31] A.N. Strahler, Hypsometric (area-altitude) analysis of erosional topology, Geolsoc. Am. Bull., 63 (1952) 1117–1142.
[32] M. Almazroui, M. Nazrul Islam, K.S. Balkhair, Zekâi Şen, A. Masood, Rainwater harvesting possibility under climate change: a basin-scale case study over western province of Saudi Arabia, Atmos. Res., 189 (2017) 11–23.
[33] R. Sluiter, Intern Rapport; IR 2009-04, Interpolation Methods for Climate Data, Literature Review KNMI, R&D Information and Observation Technology De Bilt, 19 November Version 1.0, 2008, pp. 1–23.
[34] https://glovis.usgs.gov (USGS, 2019)
[35] Y. Al-husban, Urban expansion and shrinkage of vegetation cover in Al-Balqa Governorate, the Hashemite Kingdom of Jordan, Environ. Earth Sci., 78 (2019) 620.
[36] A. AL-Taani, Y. Al-husban, I. Farhan, Land suitability evaluation for agricultural use using GIS and remote sensing techniques: the case study of Ma'an Governorate, Jordan, Egypt. J. Remote Sens. Space Sci., 24 (2021) 109–117.
[37] S. Chowdhury, M. Al-Zahrani, Implications of climate change on water resources in Saudi Arabian, Arabian J. Sci. Eng., 38 (2013) 1959–1971.