Arab J Geosci (2016) 9: 92
DOI 10.1007/s12517-015-2021-2

ORIGINAL PAPER

Towards a sustainable capital city: an approach for flood management and artificial recharge in naturally water-scarce regions, Central Region of Saudi Arabia

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Received: 3 December 2014 / Accepted: 10 September 2015 / Published online: 19 February 2016

Abstract Flash floods occur periodically on Riyadh province, Saudi Arabia, due to various factors, including rugged topography and geological structures. Each year, it results tremendous loss of life and property damage across a wide area. The present study aims to identify potential suitable areas for stormwater management in Riyadh province-Saudi Arabia using a GIS-decision support system (DSS), in addition, to determine the runoff coefficient and the runoff depth for different land cover/use classes and different soil type. Moreover, it aims to study the effect of the Riyadh metro project in the generation of flash floods around the proposed metro lines. The results of the spatial distributions of modelled annual runoff depth varied from 9 to 180 mm/year, and annual runoff depth around the proposed metro lines ranged from 70 to 120 mm/year. The major cause of floods in Al-Riyadh province is the occurrence of extremely heavy rainfall over a short period and low water absorptive capacity of soil, leading to an increased overland flow. Therefore, despite the total rainfall amount being relatively small in Riyadh province, Saudi Arabia, the rainfall event can be very intense, hence causing problems of flooding. The high-potential risk of flash floods is within areas around line 1, 2, 4, and 6. The analysis indicates that construction of the Riyadh Metro will lead to an annual increase in the flash flood generation in the urban regions. The DSS was implemented to obtain suitability maps and to evaluate the existing SWH/Groundwater recharge (GWR) structures in the study area. The DSS inputs comprised maps of rainfall surplus, slope, runoff coefficient (RC), land cover/use, and soil type. Based on an analytical hierarchy process analysis taking into account five layers, the spatial extents of SWH suitability areas were identified by multi-criteria evaluation. The spatial distribution of the classes in the suitability map showed that the excellent and good areas are mainly located in the northeastern and northwestern parts of the study area. The southeastern and west southern parts almost have the same categories dominated by moderate and poor and unsuitable areas. On average, 22.17 % (84,356 Km^2) and 31.56 % (120,085 Km^2) of the study area are classified as excellent and good for SWH, respectively, while 23.98 % (91, 243 Km^2) and 22.28 % (84,775 Km^2) of the area are classified as moderately suitable and poorly suited and unsuitable, respectively. Most of the areas with excellent to good suitability have slopes between 2 and 8 % and are intensively cultivated areas. Rainfall in these areas ranges from 120 to 230 mm. Most of the existing SWH/ GWR structures that are categorized as successful were within the excellent (89.1 % of the structures) areas followed by good suitable (10.9 of the structures). Overall, results indicated that wadi Hanifah and Wadi Nisah have a moderate vulnerability to flooding, with high vulnerability in the northeast part of Al-Riyadh province. The use of a number of SWH sites in the excellent areas is recommended to ensure successful implementation of SWH systems.

Keywords Flash floods · Stormwater harvesting · Groundwater recharge · Riyadh Metro · Analytic hierarchy process · Decision support system

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Introduction

Flash floods in Saudi Arabia are considered as one of the most serious environmental problems; they are among the most catastrophic natural extreme events that present a potential threat to both lives and property. These floods result from severe thunderstorms, which can precipitate large amounts of rainfall in short periods of time. The flash floods can help to recharge the subsurface alluvium aquifer. The volume of infiltration from floods is a major source of groundwater replenishment to unconfined aquifers in arid regions. Impounding the floods with surface dams or successive dikes could increase groundwater recharge significantly (Sirdaş and Şen 2007). On the other hand, stormwater harvesting (SWH) can provide an independent water supply during regional water restrictions, and in developed countries, it 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 groundwater levels to be maintained. The Kingdom of Saudi Arabia is one of the hottest and driest subtropical desert countries in the globe. With an average of 112 mm of precipitation per year (Mahmoud and Alazba 2014), much of the Kingdom falls within the standard definition of a desert. The exploitation of subsurface water from deep aquifers also depletes resources that have taken decades or centuries to accumulate and on which the current annual rainfall has no immediate effect (Mahmoud et al. 2014a; Mahmoud and Alazba 2014). Water limitations are particularly severe in the Kingdom of Saudi Arabia, where agriculture is almost completely dependent on groundwater, which is difficult and expensive to obtain. Owing to such limitations in water resources and the potential increase in the area under cultivation, it is necessary to develop an alternative supplementary water source. SWH may help build up water supplies and achieve a sustainable development of water resources in the region. Against the background of climate change and water shortage in the Kingdom, stormwater harvesting assumes importance in meeting the great need for new water supplies. Stormwater harvesting is now adopted in many urban areas for increasing the ground recharge as well as for other purposes such as achieving sustainable development. SWH is being promoted in the Kingdom to avoid severe drought conditions.

In the past, different forms of SWH 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 (Zaunderer and Hutchinson 1988), and in southern Tunisia (Pacey and Cullis 1986). Reiz et al. (1988) recognized the importance of traditional, small-scale SWH systems in sub-Sahara Africa and, more recently, those associated with buildings located in urban areas (Gould and Nissen-Petersen 1999). A vast array of SWH systems and structures are currently in use to address a wide variety of applications (Fewkes 1999; Gould and Nissen-Petersen 1999; Weiner 2003; Mahmoud 2014a; Mahmoud et al. 2014a; Mahmoud and Alazba 2014). The numerous advantages and benefits already ascribed to SWH (Jackson 2001; Krishna 2003; Mahmoud et al. 2014a) are sufficient to render SWH an important tool in achieving water resource management solutions in the face of a changing climate. Studies of ecological and hydrological interactions may determine resource use and influence vegetation composition and diversity (Ludwig et al. 2005; Yu et al. 2008). Identification of potential areas for SWH is an important step towards maximizing water availability and land productivity in semi-arid areas (Mbilinyi et al. 2007; Mahmoud et al. 2014a; Mahmoud and Alazba 2014).

More recently, studies integrating runoff modelling, remote sensing, and geographic information systems (GIS) have gained ascendance in targeting suitable areas for water recharging/harvesting structures (Mahmoud 2014a; Mahmoud et al. 2014a, b; Mahmoud et al. 2015; Mahmoud and Alazba 2014). While there exists a great deal of literature on the research and development of SWH structures, few studies delineate a methodology for the selection of suitable areas for SWH structures in arid regions based on data drawn from information technologies such as remote sensing (RS) and GIS. In a contrary trend, a study conducted in the Al-Baha region of Saudi Arabia (Mahmoud et al. 2014a) employed RS-GIS to collate and analyse land use, soil, slope, and hydrological digital elevation maps (DEM), along with satellite imagery (Landsat 5/7 TM/ETM) for the region. Similarly, Mahmoud et al. (2014a) presented a decision support system (DSS) for the identification of suitable areas for water harvesting/ GWR structures in the Jizzan region of Saudi Arabia. Another case study was developed for the Kali sub-watershed, in Gujarat, India, as a part of the Mahi River Watershed (Ramakrishnan et al. 2008). The parameters generally employed in identifying suitable areas for SWH is 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 areas for SWH technology implementation. With the goal of improving an agriculture potential limited 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. Gupta et al. (1997) used a GIS system to digitize information on the topography and soils and thus create a GIS database. Land cover information was derived from 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 in 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. 2014b). 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 SWH areas 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 SWH 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 areas for various SWH/recharging structures in the Kali watershed, Dahod district, Gujarat, India. Similarly, Durga Rao and Bhaumik (2003) identified land use, soil, slope, runoff potential, proximity, geology, and drainage as criteria to identify suitable areas for SWH in the wetlands of the Sunderban delta of West Bengal, India. Kahinda et al. (2008) used physical, ecological, and socioeconomic factors (land use, rainfall, and soil types, 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 approach introduced by Saaty (1977, 1980, 1990, 1994, 2008). A type of GIS-based MCDM that combines and transforms spatial data (input) into result decisions (output), the AHP uses geographical data, 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 uni-dimensional values of alternative decisions.

The purposes of this paper are to: (1) Identify potential suitable areas for stormwater management in Riyadh province, Saudi Arabia using remote sensing and geographic information systems. (2) Determine the runoff coefficient and runoff depth for different land cover/use classes and different soil types using RS and GIS in Riyadh region. (3) Study the impact of the Riyadh metro project in the generation of floods around the proposed metro lines and in the entire province. (4) Evaluate existing artificial recharge and rainwater harvesting structure in the study area,

This study will help decision makers and water resources planners in Riyadh region, Saudi Arabia to plan, stormwater, harvesting structure in suitable areas to reduce urban flooding, which is a common issue in Riyadh during very heavy rainfall.

Study area and methodology

Study area

Al-Riyadh Province (Fig. 1) is the second largest province in Saudi Arabia. It has an area of 380497.8 km^2 and a population of 6,777,146 (2010), making it the second largest province in terms of both area (behind the Eastern Region) and population (behind Makkah Region). It is situated in the center of the Arabian Peninsula (24° 38′ N 46° 43′ E) on a large plateau. Its capital is the city of Riyadh, which is also the national capital. The recently completed and ongoing constructions boast of having some of the ambitious architectural designs in the Kingdom. Such as, King Abdullah Financial District Metro Station and a host of other forthcoming proposed projects. Riyadh is the capital and largest city of Saudi Arabia. It is also the capital of Riyadh Province. The average high temperature in July is 42.6 °C. Winters are warm with cold, windy nights. The overall climate is arid, and the city experiences an annual rainfall ranges from 41 to 230 mm/year.

Methodology

The delineation of suitable areas for stormwater management is a multi-criteria problem. The major steps in mapping in this study were as follows: (i) selection of criteria, (ii) assessment of the suitability levels of the criteria for SWH, (iii) assignment of weights to these criteria, (iv) collection of spatial data for the criteria through various sources, 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 following five criteria were selected for identifying potential areas for flash floods management and SWH:

- Soil type map
- Land cover and land use (derived from available RS data).
- Slope (i.e., topography)
- Runoff coefficient
- Rainfall surplus precipitation

The criteria and their application for mapping the flash floods management and SWH potential in the region are presented in Fig. 2. Because of the different scales on which the criteria measured, the values contained in the criterion maps have to be converted into comparable units for SMCE. Therefore, the criteria maps were re-classed into four comparable units or suitability classes, namely: 5 ("excellent"), 4 ("good"), 3 ("moderate"), 2 and 1 ("poor and unsuitable"). The suitability classes were then used as the basis to generate the criteria map.

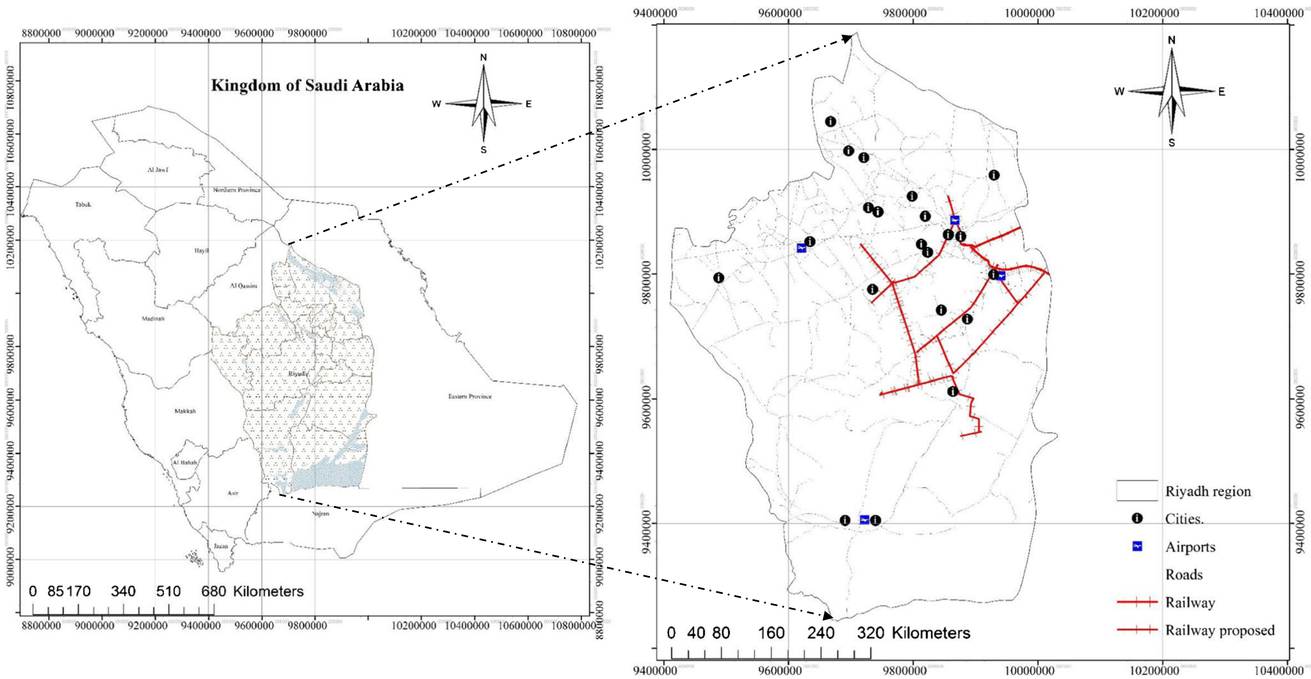


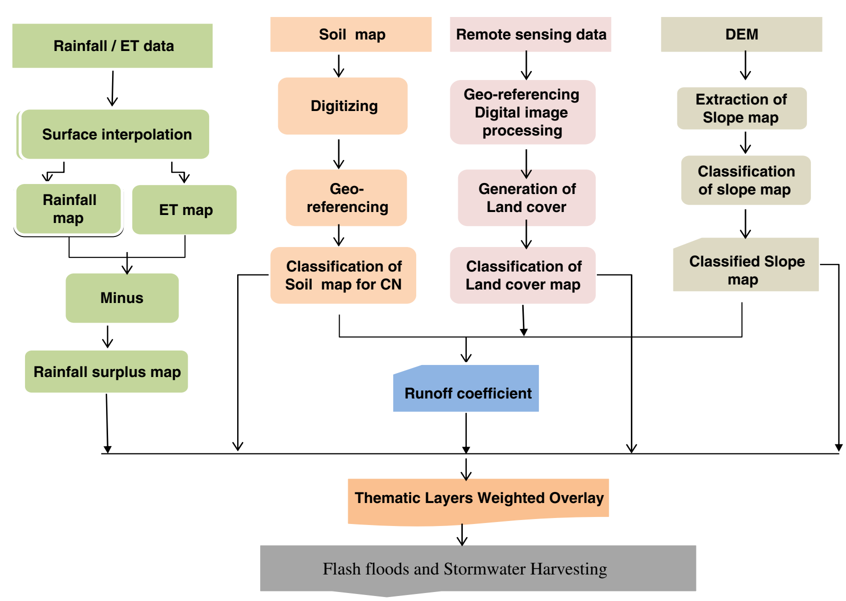
Fig. 1 A location map of the study area

Data pre-processing and analysis

Soil type map

The soil type map of the study area (Fig. 3) was prepared from the published soil map obtained from Ministry of Agriculture. The study area covered by six different soil types: Arenosols, Lithosols, Miscellaneous land units, Regosols, Solonchaks, and Yermosols. Arenosols soil is a sandy soils with little profile development; this type of soil has high permeability, low water storage capacity, and low biological activity, which all promote decalcification of the surface layers of Arenosols in the dry zone like Riyadh province, even though the annual precipitation sum is extremely low. Lithosols soil is a thin soils over rock derived from sedimentary sandstones "Shallow soils with rock <10 cm from the surface"; its material is usually coarse textured with a very low clay content and minimal organic matter accumulation on the surface. Lithosols are strongly acid and have a low water holding capacity due to the coarse texture, abundant stones, and shallow depth. However, infiltration rates can be high. Miscellaneous land units consist of dunes, salt flats, and rock debris or desert

Fig. 2 The work flowchart



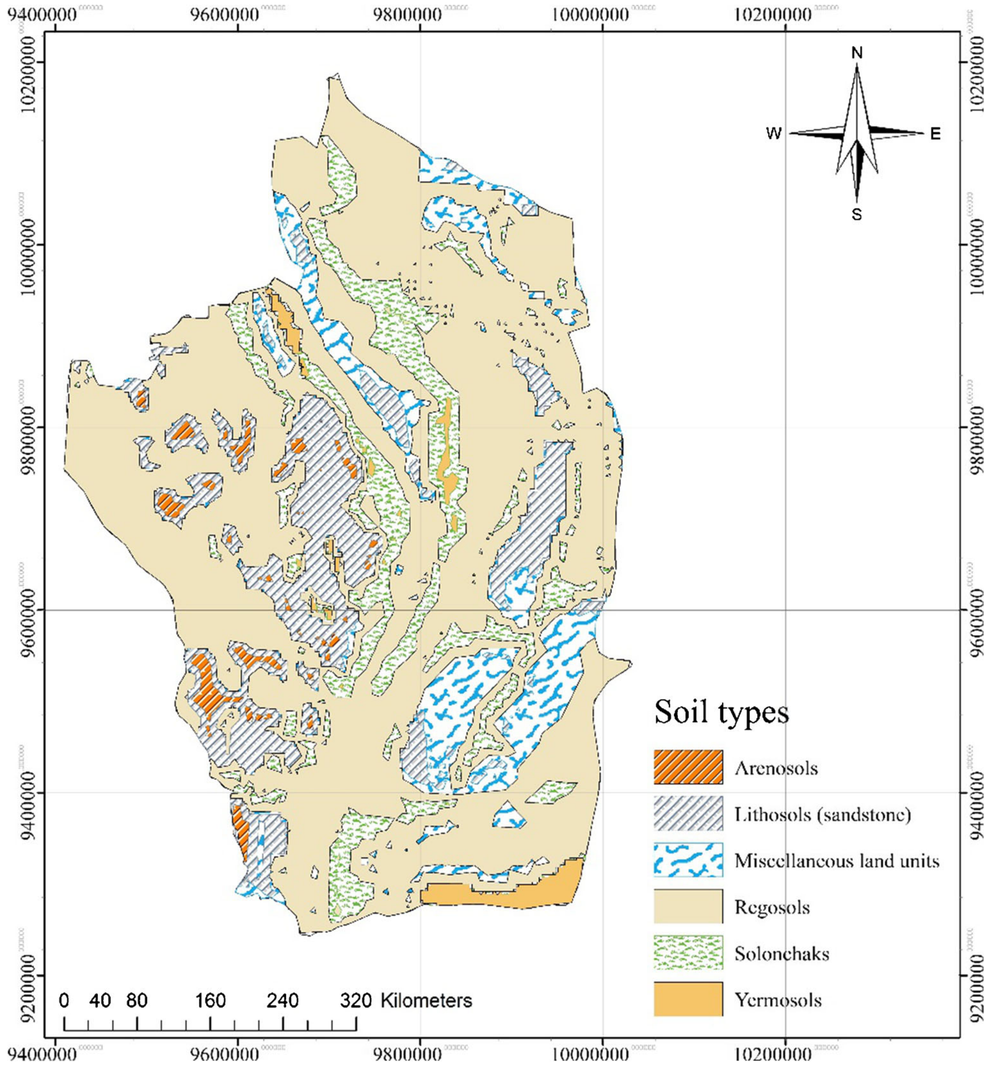


Fig 3 Soil type map for the study area

detritus. Regosols soil consists of a surface layer of rocky material, and its texture is mainly coarse texture. Solonchaks: Salty soil with little horizon development. Yermosols (aridic soils) have an argillic (clay accumulation), likely formed during a period with a wetter climate. Water deficiency is the dominant characteristic of Aridisols with adequate moisture for plant growth present for no more than 90 days at a time. Crops cannot be grown in these soils without irrigation. Aridic soils are commonly light in color, and low in organic matter content. Lime and salt accumulations are common in the subsurface horizons.

The majority of the study area is dominated by Regosols soil, which is about 62.6 %. This soil was classified as good for groundwater potential zones due to its coarse texture and high infiltration rate followed by Lithosols soil, which covers about 12.6 % of the total area. This soil is mainly located in the central regions of the study area. Moreover, this soil was categorized as very good for groundwater potential zones due to its coarse texture, very low clay content, and low water holding capacity. Miscellaneous land units are found along the southeastern and northwestern parts of the study area; it represents 10.3 % of the total area and classified as moderate recharge zones. Arenosols soil only occupied 1.4 % of the study area. This type of soil has high permeability, low water storage capacity, and low biological activity. Therefore, it was classified as excellent recharge zones according to their influence on groundwater occurrence and excellent rate of infiltration. Solonchaks (salty soil) and Yermosols soils occupied 11.2 and 1.9 % of the total area. The infiltration rate of this soil is moderately low due to clay content. Clay soil is classified as poor due to poorly drained, slowly permeable, severely eroded, and low hydraulic conductivity (Chowdhury et al. 2009). Therefore, these soils were considered as moderate and poor recharge areas respectively. The areas covered by the different soil types are presented in Table 1.

Table 1 Areas covered by the different Soil types

Soil type	Area (Km^2)	% of total area
Arenosols	5430.3	1.4
Lithosols	47874.9	12.6
Miscellaneous land units	39032.2	10.3
Regosols	238323.6	62.6
Solonchaks	42783.6	11.2
Yermosols	7053.1	1.9
Total	380497.8	100

Land cover/use map

A Landsat TM/ETM image for the year 2013 [2013, with 30 m resolution] was incorporated with collected data and ultimately served in categorizing land use and land cover (LULC). Iso Cluster unsupervised classification and maximum likelihood classification function in the ArcGIS Spatial Analyst were used for the unsupervised classification. Training samples were collected during field surveys to create spectral signatures (i.e., reflectance values) for the supervised classification to identify what the clusters represented (e.g., water, bare earth, dry soil, etc.). The LULC map classified into 6 main classes (Fig. 4). Urban and built-up land accounts for about (36699.2 Km^2) 9.65 % of the total area. While irrigated cropland and pasture accounts for about 43642.6 Km2 or about 11.47 % of the total area, bare soil occupies 177248.4 Km^2 (46.58 % of the total area). In addition, sparsely vegetated land, shrubland, and mixed tundra accounts for about 28531.1 Km^2 (7.5 %), 67107.8 Km^2 (17.64 %), and 27268.6 Km^2 (7.17 %) of the total area, respectively. The areas covered by each land cover and land use are presented in Table 2.

Assessing the accuracy of a land cover map requires ground truthing. Georeferenced ground truthing points were collected using a GPS unit and used to validate the land cover and land use maps. Validation analysis was performed using the Kappa Agreement Index (KIA) where a value exceeding 0.8 indicates a high classification performance (Jensen 2005). The overall kappa statistic was 0.87, indicating that the classification of the land use and land cover map was accurate. Figure 4 shows the proposed project for Al-Riyadh Metro. The contracts for the design and construction of Riyadh's

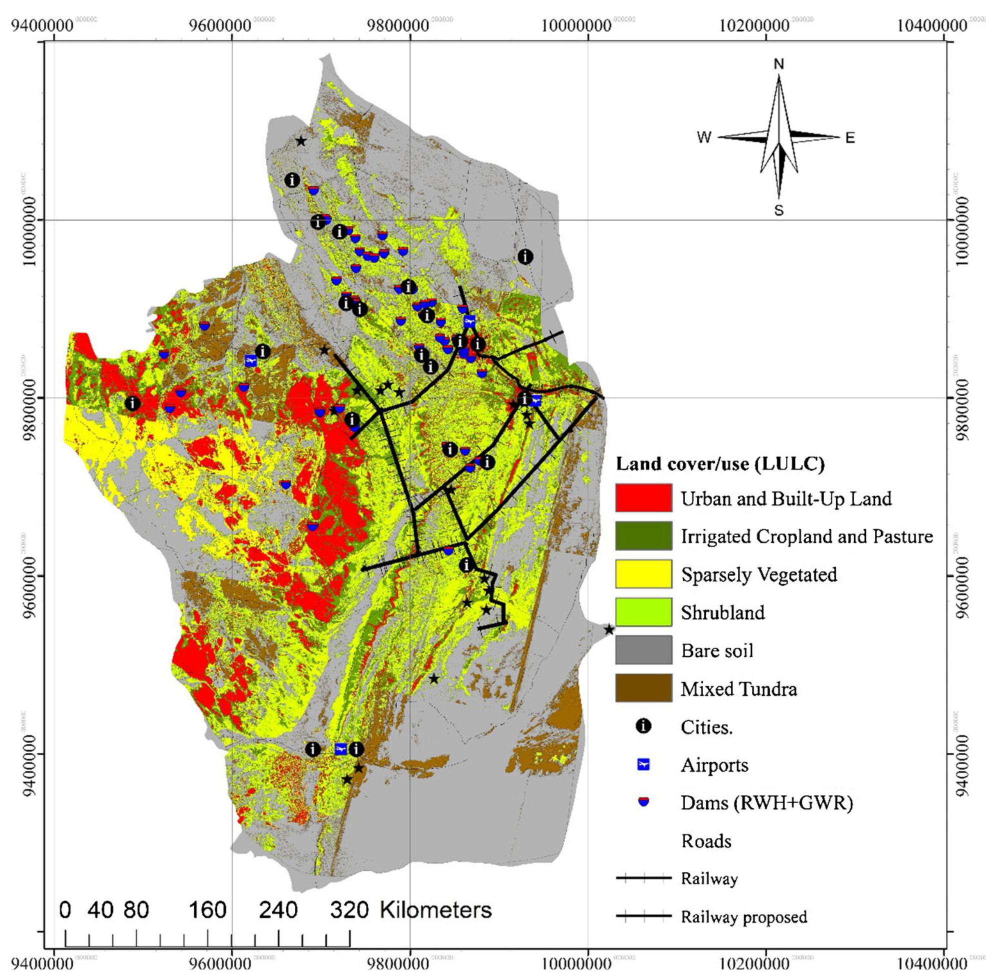


Fig 4 An LULC map for the study area

Table 2 Areas covered by the different land cover and land use

Land cover/land use	Area (Km^2)	% of total area
Urban and built-up land	36699.2	9.65
Irrigated cropland and pasture	43642.6	11.47
Sparsely vegetated	28531.1	7.50
Shrubland	67107.8	17.64
Bare soil	177248.4	46.58
Mixed tundra	27268.6	7.17
Total	380497.8	100

new US$22.5 billion metro system, the next major step in the development of the largest public transport project in the world—the Riyadh Public Transport Project. The project encompasses a citywide metro, bus network, and park and ride services. This project will connect most of the capital together and make the transportation process easier from one place to another in a limited time. It will lead to urban expansion and give the people the opportunity to move to farther places from their work to establish new house. However, it may increase the prices of new real estate in the region.

Slope

A DEM with 30-m resolution developed at the KACST was used to generate the slope map for Al-Riyadh. Sinks and flat areas were removed to maintain the continuity of flow of water to the catchment outlets (Fig. 5). Slope maps (Fig. 6) were generated for the study area based on Al-Riyadh Filled DEM for identifying potential SWH areas and for determining the potential runoff coefficient (PRC).

Potential runoff coefficient

Potential runoff coefficient (CN) is a hydrologic parameter used to describe the stormwater runoff potential for a given drainage area. It is a function of land use, soil type, and soil moisture. The modelled curve number for this study was developed using the previous three maps (LULC, soil types, and slope) based on the study conducted by Mahmoud et al. (2014a). The curve number map (Fig. 7) shows a variation in the values of runoff from as low as 0.23 to a maximum of 1.0. These values indicate the potential amount of annual

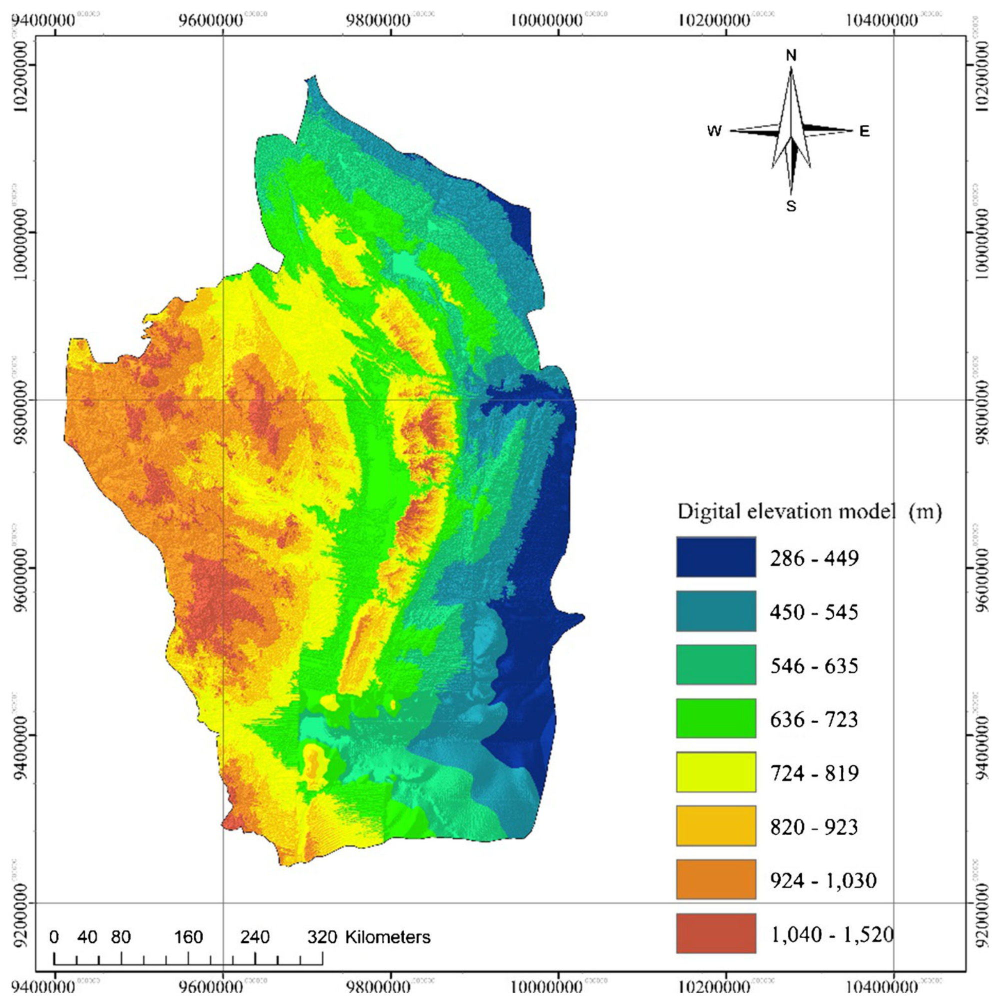


Fig. 5 The digital elevation model of the study area

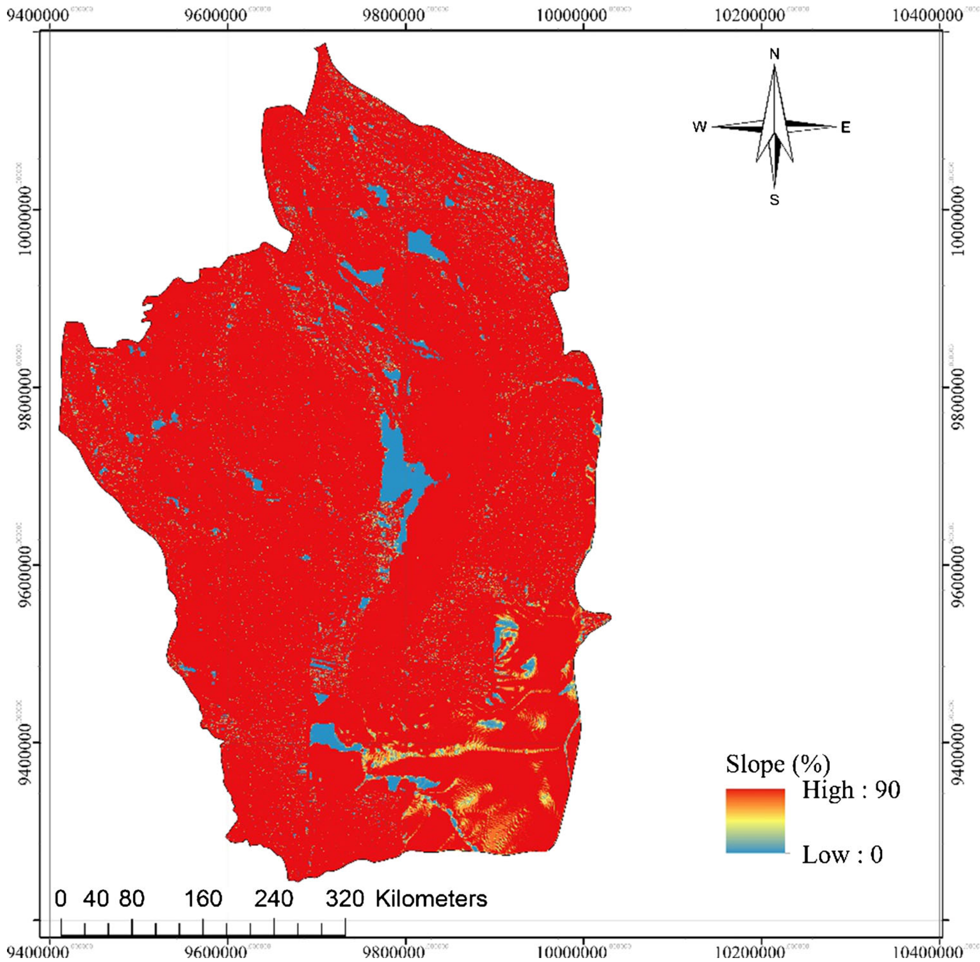


Fig. 6 A slope map for the study area

rainfall that can be harvested and used for agriculture, potable, and groundwater recharge. The potential runoff coefficient approaches 0 when slope is negligible and 1.0 when the slope is infinite. In addition, the changing magnitude of the potential runoff coefficient is decreasing along with the increasing of surface slope. It confirms that the runoff volume for a certain amount of rainfall is less or even not affected by slope beyond a critical slope (Sharma 1986; Mahmoud et al. 2014a, 2015; Mahmoud 2014b). It is clear from Fig. 7 that runoff coefficient tends to increase in urban areas due to soil and land cover properties. The highest runoff coefficient is in the southeastern and southwestern parts of the capital, which contain very important infrastructures like airports and administration offices, with a runoff value ranges from 0.4 to 1. Towards the north and east, runoff coefficient is much lower than other places, due to the domination of agriculture land and runoff harvesting structure.

Rainfall surplus

Climatic data were obtained from meteorological department, Ministry of Agriculture and Ministry of Water and Electricity, for a period of 32 years to obtain the long-term annual rainfall for the study area. These data were interpolated by using the following sources: (i) satellite images for monthly global precipitation from (1979 to 2009) obtained from the World Data Center for Meteorology. (ii) NASA Tropical Rainfall Measuring Mission (TRMM) Monthly Global Precipitation Data from (1998–2010) obtained from NASA GES Distributed Active Archive Center.

Penman-Monteith method (Monteith 1965) was used for estimating the potential Evapotranspiration (ET) as follows:

$$E_T = \frac{\Delta R_n + (e_a - e_d)^* \frac{\rho^* c_p}{r_a}}{\lambda\left(\Delta + \gamma^*\left(1 + \frac{r_s}{r_a}\right)\right)} \tag{1}$$

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 the surfaces of the leaves and soil (s/m)
- r_a Net resistance to diffusion through the air from surfaces to height of measuring instruments (s/m).

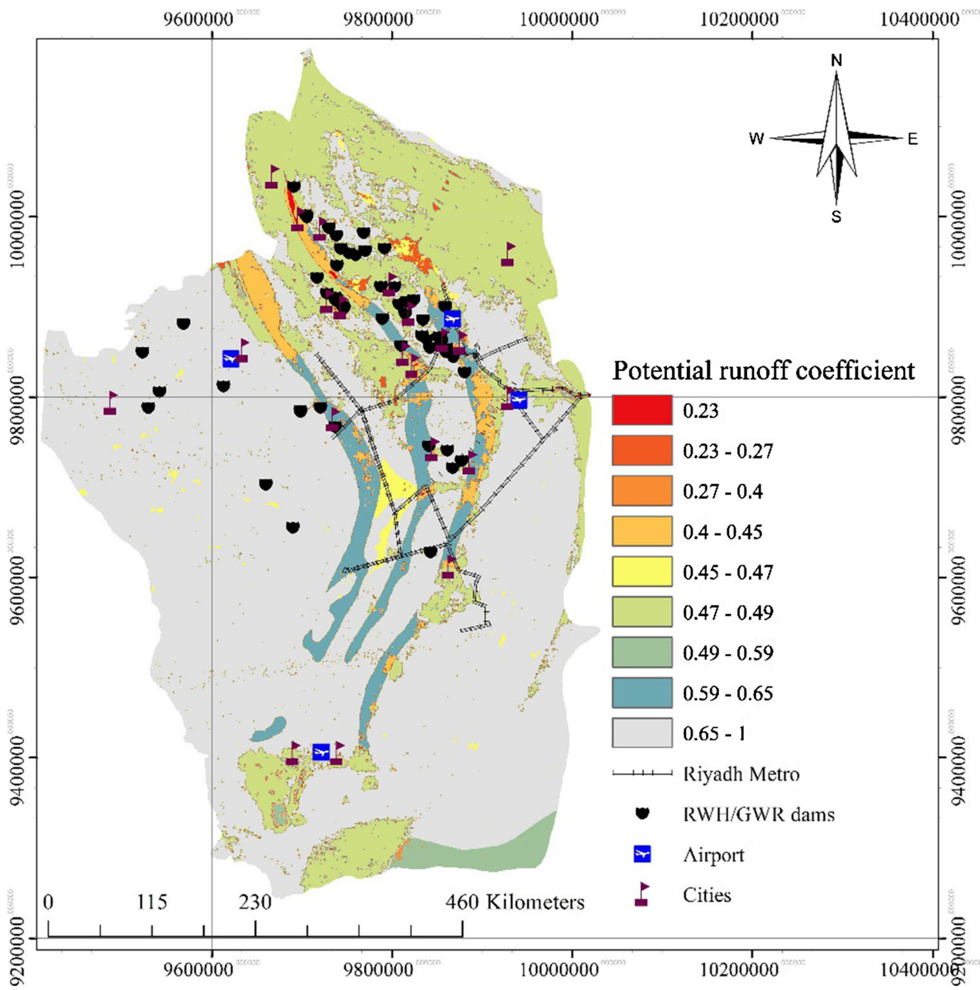


Fig. 7 Distribution of PRCs

γ Hygrometric constant
Δ de/dT
e_a Saturated vapor pressure at air temperature
e_d Mean vapor pressure

ET refers to the total amount of water vapor enter 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 major scientific challenge for many years until Penman (1948) came up with the combination approach, which solved the problem for open water or wet soil surface, and Penman (1953) further improved the model for unsaturated surface of single leaf by introducing resistance. Monteith (1965) applied the Penman Equation for the canopy. The Penman equation since then became the famous Penman-Monteith equation. The amount of ET is equally expressed in two units: the amount of water left the surface in ET (mm) or the amount of energy used in ET (W/m^2). The rainfall surplus (P-ET) map (Fig. 8) calculated by subtracting long-term average monthly evapotranspiration values of the precipitation for all meteorological stations covering the period from 1950 to 2013. The annual rainfall surplus calculated at each meteorological station by adding only the positive values of the difference (P-ET), spatial distribution of rainfall surplus map generated by interpolating previous data values using ArcGIS.

Assessment of suitability level and weights to different criteria

Areas with large rainfall surplus have a high suitability rank since the surplus ensures the availability of runoff for SWH and flash flood generation. SWH is generally more suitable for flat areas with a low slope; however, note that a slight slope is needed for better capturing the runoff. Therefore, areas with slopes of 2 to 8 % have a high suitability rank. Runoff index when RC > 0.5 is indicative of a potential area for SWH. Mahmoud (2014a) gives a detailed analysis of the suitability rankings. The values for each suitability category were scaled from 1 to 9 and are based on the criteria of Mahmoud (2014a). The method has been found to be robust and reliable (Russell et al. 1997; El-Awar et al. 2000; Store and Kangas 2001). The

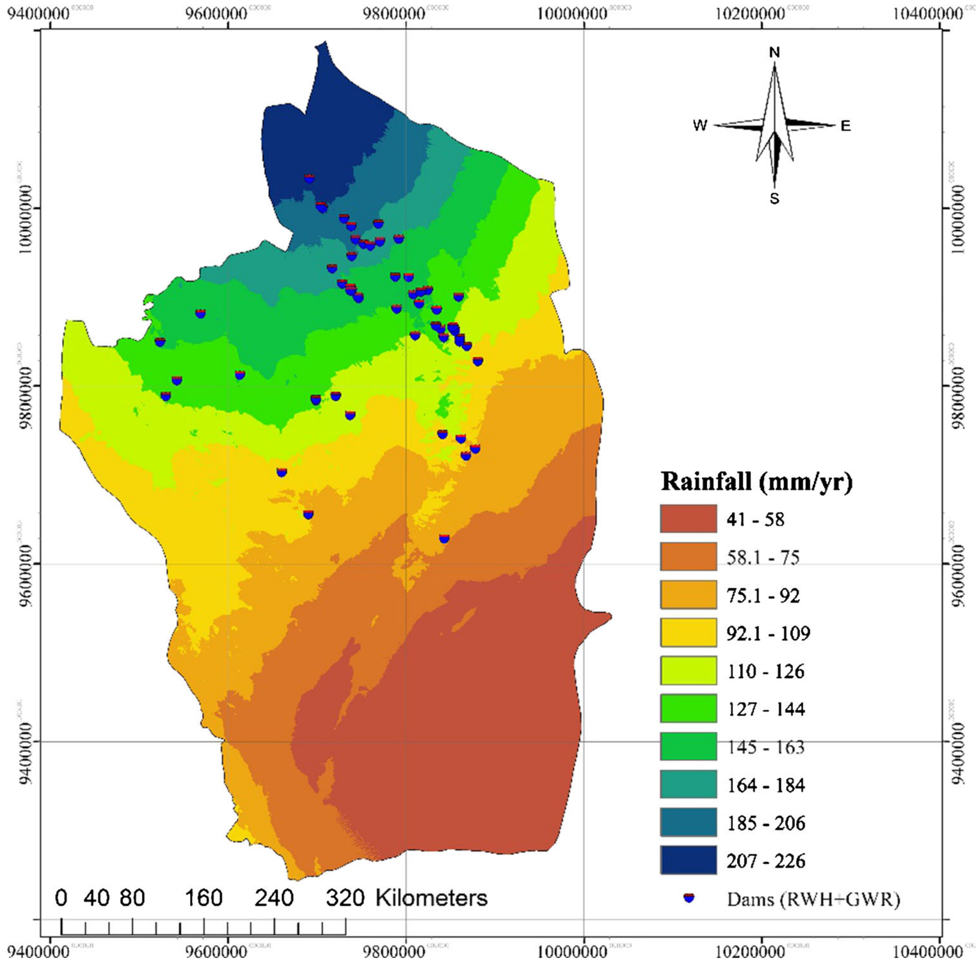


Fig. 8 The rainfall surplus map for the study area

suitability rankings for soil types, rainfall surplus, slope, land cover, and runoff coefficient (RC) are shown in Table 3.

The criteria were assigned weights by applying the 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 is used for this calculation. The weighting procedure is based on AHP. 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, the 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 was created by setting out one row and one column for each factor in the problem (Table 4). The

Table 3 Suitability levels for different factors for Runoff and stormwater harvesting

Suitability values	5	4	3	2	1
Soil type	Fine	Fine and medium	Medium	Medium and coarse	Coarse
Rainfall surplus	Large surplus	Small surplus	Medium deficit	Large deficit	Very large deficit
Slope (%)	2–8	8–15	0–2	15–30	>30
Land cover	Intensively cultivated	Moderately cultivated	Forest, exposed surface	Mountain	Water body, urban areas
Runoff index	0.7–0.82	0.6–0.7	0.4–0.6	0.27–0.4	0–0.27

Table 4 Pairwise comparison matrix for Runoff and stormwater harvesting

	Soil type	Land cover	Slope	Rainfall surplus	Runoff
Soil type	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

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, which shows the degree of consistency achieved when comparing the criteria or the probability that the matrix rating was randomly generated, was 0.02, and this indicates acceptable consistency (Saaty 1977).

GIS-based suitability model and SWH suitability maps

A suitability model was developed using the model builder of ArcGIS 10.1. The model generates suitability maps for SWH by integrating different input criteria maps using Weighted Overlay Process (WOP) by utilizing both vector and raster databases. With a weighted linear combination, criteria are combined by applying a weight to each, and the results are summed up to yield a suitability map using the WEIGHT module of IDRISI software (Table 5).

Results and discussion

The major cause of floods in the study area is the occurrence of extremely heavy rainfall over a short period and low water absorptive capacity of soil, leading to an increased overland flow. This excess overland flow is concentrated by the topography and converges on the area channel network, generating in a flood flow. Therefore, despite total rainfall amount being relatively small in Saudi Arabia, the rainfall event can be very intense, hence causing problems of flooding. Spatial and quantitative runoff depth distribution (Fig. 9) has been identified in Al-Riyadh region using Al-Riyadh runoff coefficient and rainfall surplus (which is the effective rainfall after excluding annual evapotranspiration). Results of spatial distributions of modelled runoff coefficient show a variation from as low as 0.23 into a maximum of 1 and was observed due to divergence in topography and climate in Al-Riyadh region, where the largest rainfall was observed in the north. These values are relatively well explained by mean annual precipitation. Runoff coefficients tend to increase with mean annual precipitation. The significance of this relationship means that mean annual precipitation influences the distribution of runoff coefficients not only through the characteristics of the flood-generating storm events, but also by controlling the variability of the initial conditions and, at longer time scales, likely by controlling the geomorphological structure of catchments, through soil formation and erosion processes. Surface runoff in Riyadh varies from as low as 9 to a max of 180 mm/year. Its value tends to increase in urban areas due to soil and land cover properties, which lead to flash floods that occur periodically in Riyadh province, Saudi Arabia, due to several factors, including rugged topography, heavy rainfall events, and geological structures. Each year, it results much damage to people's life and properties.

Table 5 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

The highest runoff depth is within the southeastern and southwestern parts of the capital, which contain very important infrastructures like airports and administration offices, with surface runoff value ranges from 71 to 180 mm/year. Towards the north and east, runoff volume is much lower than other places due to the domination of agriculture land and runoff harvesting structure. However, these areas recently witnessed unpredicted flash floods with huge damage to infrastructure and major roads. The northern areas of Al-Riyadh province have the highest potential risk of flood generation with a large flash floods record, which always causes traffic jams and suspend studies in schools and universities for the day due to its serious damage. Surface runoff depth in these areas, as shown in Fig. 9, ranges from 110 to 180 mm/year. A huge amount, which can cause so much damage in relation to soil type, makes the soil layers unstable. An example of that is a Wadi Nimar valley, which is surrounded by steep banks and can therefore suddenly fill with water in case of rainfall. This amount of flash floods in Riyadh caused power cuts in parts of the city during the past years. In addition, shops and markets had also flooded. For future prospective, if the situation will remain the same as the proposed project for Al-Riyadh Metro, this project is the next major step in the development of the largest public transport project in the world—the Riyadh Public Transport Project—which will face an annual runoff ranges from 70 to 120 mm/year. The higher-potential risk of

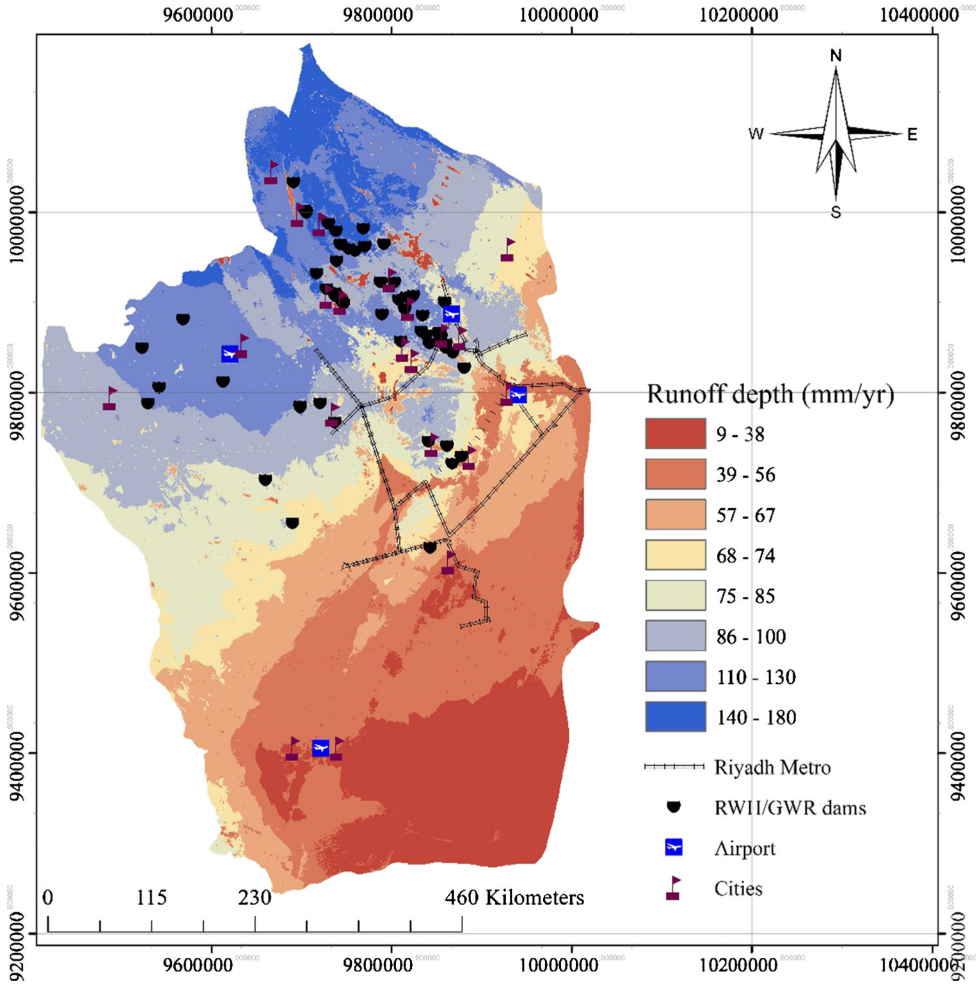


Fig. 9 Annual runoff depth map for the study area

flash floods is within areas around line 1, 2, 4, and 6. The analysis shows that construction of the Riyadh Metro will lead to an annual increase in the flash flood generation in the urban areas. In addition, it will lead to urban expansion, which is a supporting point in increasing chances of flooding.

Delineation of suitable areas for stormwater harvesting (SWH) in Al-Riyadh region can provide the long-term sustainable solutions to flash floods, in addition to increasing land productivity in arid semi-arid regions through artificial recharge. Figure 10 shows the suitability map for SWH and flood risk management with four suitability classes—excellent, good, moderate, and poor and unsuitable suitability. The areas shown in the map are those identified by DSS with either very high or high suitability levels for SWH. The spatial distribution of the classes in the suitability map showed that the excellent and good areas are mainly located in the northeastern and northwestern parts of the study area. The southeastern and west southern parts almost have the same categories dominated by moderate and poor and unsuitable areas. This is attributed to differences in spatial variability in parameters important for identifying potential areas for SWH technologies, including soil, rainfall surplus, and slope. The potential suitable areas for different types of SWH technologies as determined by the DSS for the study area are shown in Table 6. On an average, 22.17 % (84,356 Km^2) and 31.56 % (120,085 Km^2) of the study area are classified as excellent and good for SWH, respectively, while 23.98 % (91,243 Km^2) and 22.28 % (84,775 Km^2) of the area are classified as moderately suitable and poorly suited and unsuitable, respectively.

The potential areas for SWH technologies identified and shown in the Fig. 10 reflect specific suitability levels of factors and weight of factors. For example, most suitable areas for SWH are located in the higher rainfall areas with slopes ranging from moderately undulating to steep. These results agree with field observations, which indicated that most of the areas with excellent to good suitability have slopes between 2 and 8 % and are intensively cultivated area. The rainfall in these areas ranges from 120 to 230 mm. Moreover, the results agree with the findings obtained by Mahmoud et al. (2014b). Moreover, Fig. 10 shows historical flood locations in the study area in addition to the suggested locations for flood control. Most of the historical flood locations fall near excellent and

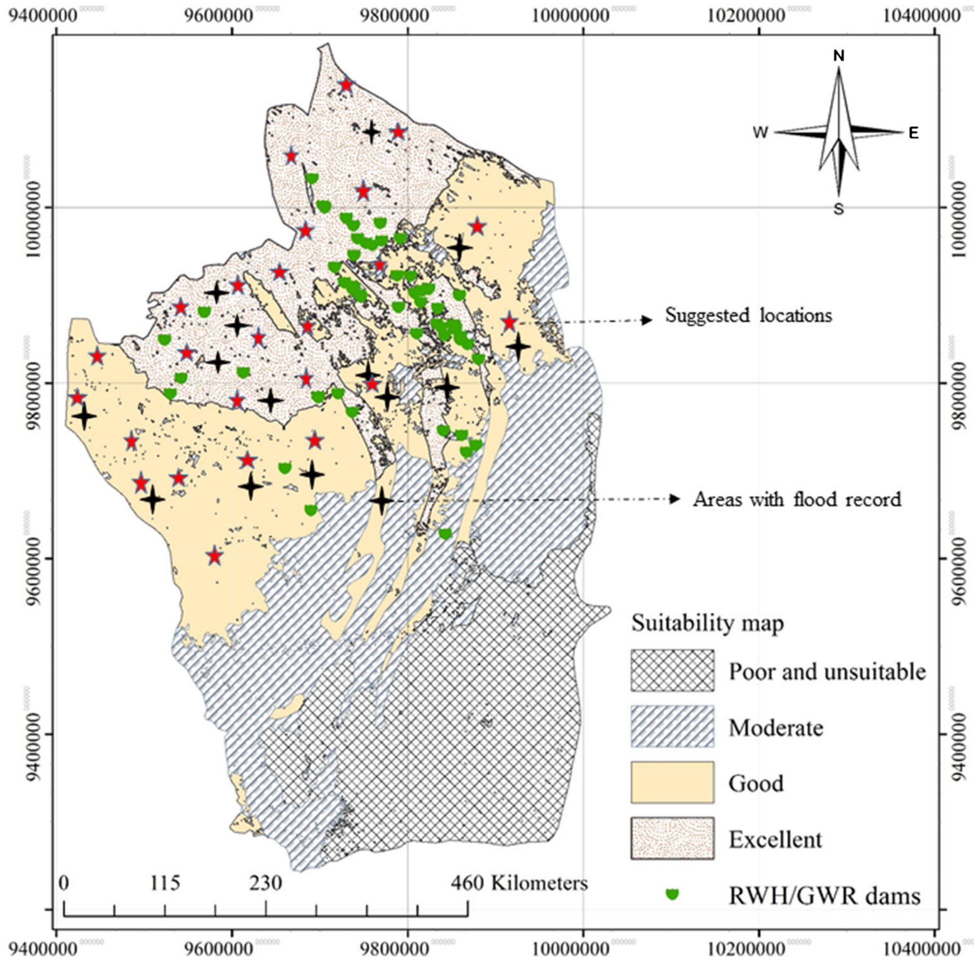


Fig. 10 The suitability map for SWH for the study area

good areas for SWH. The use of a number of SWH sites in the excellent areas is recommended to ensure successful implementation of SWH systems

Many regions of Saudi Arabia as well as of developing countries do not have sufficient historical records and detailed runoff information needed for physically based distributed models. In these cases, this study can provide a better solution for flood management programs following the recommendation of (Mahmoud et. al 2014b; Mahmoud and Alazba 2014).

During the field survey, 57 dams for GWR and stormwater management, including flash flood control (Table 7), were found within the study area. Here, 52 % of the existing dams were established for GWR. This is justified because the groundwater resources were depleted in the area around the dams before their construction. Such depletion over the years hindered agricultural activities in the area since the main sources of water here are groundwater wells. Furthermore, it was revealed that 48 % of these structures were established for flood control. The fact that the main purposes of most of the dams in the study area are GWR and flood control gives an indication of the importance of this study especially in Wadi Hanifah and Wadi Nisah. Wadi Hanifah is the most significant natural landmark of the region that forms with its basin and tributaries a unique 120-km-long ecological region stretching from Tuwaiq Escarpment to the open desert southeast of Riyadh. The depth of valley stream ranges between 10 and 100 m, and its width ranges from 100 to 1000 m approximately. Moreover, Wadi Hanifah, which consists of dense urban settlements and is a highly populated area, is located in moderate to high flood probability and excellent to good recharge suitability (Fig. 11), while Wadi Nisah encompasses low flood probability and good recharge suitability. Wadi Hanifah represents a natural watershed for the floods and rainwater in an area of 4000 m^2, and it has more than 40 tributaries. The most important among the Wadi's tributaries are Al-Obaitah, Al-Imariyah, Safar, Al-Mahdiyah, Beir, Laban, Namar, Al-Awsat, and Laha in the west and Al-Aysan and Al-Bathaa in

Table 6 Areas under different suitability classes

Suitability	Area (Km^2)	Percent of total area
Excellent	84,356	22.17 %
Good	120,085	31.56 %
Moderate	91,243	23.98 %
Poor & Unsuitable	84,775	22.28 %

Table 7 Existing dams in Al-Riyadh region

No	Dam name	Purpose	Design capacity, m^3	Actual capacity, m^3
1	Nemar	Groundwater recharge (GWR)	1,500,000	1,500,000
2	Huraimila	GWR	2,500,000	917,318
3	Malham	GWR	200,000	607,457
4	Laban	GWR	2,000,000	2,177,384
5	Hanifah	GWR	1,500,000	1,500,000
6	Saffar	Stormwater management (SWM)	300,000	537,766
7	Ghubaira	SWM	90,000	314,146
8	Al Hrigh	SWM	80,000	230,898
9	Al Oyaynah	GWR	1,000,000	1,000,000
10	Al Majmah	SWM	1,300,000	1,175,929
11	Al Alb	SWM	2,000,000	403,221
12	Jalajel	GWR	1,750,000	3,001,032
13	Al Ghat	GWR	1,000,000	325,100
14	Thadiq	GWR	2,000,000	1,223,601
15	Al Hayer	GWR	3,800,000	3,800,000
16	Rawdhat Sudair	GWR	3,000,000	5,686,832
17	Marrat	GWR	400,000	184,523
18	Al Safrat	SWM	1,500,000	1,373,423
19	Sadus	GWR	400,000	400,000
20	Samnan	STM	1,500,000	1,069,965
21	Al Maneh	GWR	100,000	33,945
22	Al Shuaara	GWR	1,000,000	287,165
23	Houtat Bani Tamim	GWR	3,000,000	9,910,010
24	Alamaleh	GWR	1,000,000	933,647
25	Al Munhana	GWR	1,000,000	251,705
26	Al Nasaq	GWR	1,500,000	333,423
27	Al Shammam	GWR	1,500,000	201,960
29	Al Wasiah	GWR	1,000,000	22,703
30	Durma	GWR	1,500,000	1,069,816
31	Al Quaieiah	GWR	1,500,000	598,346
32	Al Maliah	GWR	1,000,000	1,000,000
33	Al Anbari	GWR	110,000	42,703
34	Al Ghail	SWM	2,500,000	3,001,032
35	Al Hariq	GWR	6,000,000	13,575,442
36	Al Hanabeg	GWR	3,500,000	619,603
37	Hujaila	SWM	250,000	89,876
38	Ashirah	SWM	300,000	116,281
39	Al Tamriyah	SWM	1,000,000	77,157
40	Al Barrah	SWM	1,000,000	22,460
41	Athatheyah	GWR	250,000	24,822
42	Al Halifah	SWM	300,000	44,961
43	Esam	SWM	150,000	75,146
44	Al Jafinah	SWM	100,000	22,867
45	Al Mutairfiah	GWR	2,500,000	1,503,519
46	Al Muzaireiah	GWR	1,500,000	1,208,750
47	Al Hayir	GWR	1,000,000	478,418
48	Hudijah	GWR	1,500,000	844,528
49	Al Hurayek At Al Washim	GWR	1,000,000	138,692
50	Mazwi	GWR	200,000	109,212

Table 7 (continued)

No	Dam name	Purpose	Design capacity, m^3	Actual capacity, m^3
51	Budah	GWR	500,000	51,210
52	Haleifah Al Musaid	GWR	200,000	22,677
53	Lassad	GWR	1,500,000	1,000,404
54	Al Healwah	SWM	10,000,000	11,955,180
55	Al Hafairah	GWR	250,000	125,217
56	Al Mahdeyah	GWR	150,000	190,966
57	Al Thumilah	SWM	840,000	634,351

the east (Table 7). The amount of water poured into Wadi Hanifah is about 700,000 m^3. Wadi Hanifah has five sections including bed, floodplain, horizontal alluvial terraces, valleys, and branches. Many small and large villages scatter along the banks of the valley. In general, the results show that Wadi Hanifah and Wadi Nisah have a moderate vulnerability to flooding, with high vulnerability in the northeast part of Al-Riyadh province.

The availability of SWH and flood management structures in the study area supported farmers with sufficient water for irrigation and agriculture development through artificial recharge. These results agree with field observations, which indicated that most of the cultivated areas were close to GWR structures. Moreover, the results agree with the findings obtained from Jackson (2001), Krishna (2003), and Mahmoud et al. (2014a). The locations of existing SWH/ GWR dams were compared with the locations indicated on the generated suitability map by using the proximity analysis tool of ArcGIS 10.1. Most of the existing SWH/ GWR structures that are categorized as successful were within the excellent (89.1 % of the structures) areas followed by good suitable (10.9 of the structures). The validation of this model revealed that 100 % of the existing GWR/SWH structures are located in areas that fall into the good and excellent areas. This validates the database and methodology used for developing the suitability model.

Conclusion and recommendations

Delineation of suitable areas for stormwater harvesting (SWH) in Al-Riyadh region can provide the long-term sustainable solutions to flash floods, in addition to increasing land productivity in arid semi-arid regions through artificial recharge. This is especially important for Saudi Arabia, where mainly groundwater resources are used to meet the water demands for agricultural purposes. This study revealed that urban and built-up land accounts for about (36699.2 Km^2) 9.65 % of the total area. While irrigated cropland and pasture accounts for about 43642.6 Km^2 or about 11.47 % of the total

Fig. 11 Satellite image of the overall Al-Riyadh region: the *green highlights* show the surface-water runoff system and the *white line* highlighted the urban area of Al- Riyadh

area, bare soil occupies 177248.4 Km^2 (46.58 % of the total area). In addition, sparsely vegetated land, shrubland, and mixed tundra accounts for about 28531.1 Km^2 (7.5 %), 67107.8 Km^2 (17.64 %), and 27268.6 Km^2 (7.17 %) of the total area, respectively.

The northern areas of Al-Riyadh province have the highest potential risk of flood generation with a large flash floods record. In addition, results revealed that wadi Hanifah and Wadi Nisah have a moderate vulnerability to flooding, with high vulnerability in the northeast part of Al-Riyadh province. Therefore, the generated annual runoff depth map can be used to plan and set up flood control structure. This map is very useful to Saudi Civil Defence authority where it can be used in rescue operations during flash flood events. For future prospective, if the situation will remain the same as the proposed project for Al-Riyadh Metro, it will face an annual runoff ranges from 70 to 120 mm/year. The higher-potential risk of flash floods is within areas around line 1, 2, 4, and 6. The analysis shows that construction of the Riyadh Metro will lead to an annual increase in the flash flood generation in the urban areas. In addition, it will lead to urban expansion, which is a supporting point in increasing chances of flooding.

In the present study, suitable locations for SWH and GWR were identified and the existing SWH/GWR structures in Al-Riyadh Province was evaluated using a suitability model. The suitability map generated classifies the region into four suitability classes—excellent, good, moderate, and poor and unsuitable. This map can be used to plan and set up SWH/GWR structures at the most suitable locations to ensure their successful application for providing water for agriculture and for flood control. This study is in great help to decision makers and water resources planners in Riyadh region, Saudi Arabia to plan, stormwater, harvesting structure in suitable areas to reduce urban flooding, which is a common issue in Riyadh during very heavy rainfall.

Acknowledgments This project was financially supported by King Saud University, Deanship of Scientific Research, College of Food and Agricultural Sciences Research Centre.

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