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ORIGINAL ARTICLE

Optimization of area–volume–elevation curve using GIS–SRTM method for rainwater harvesting in arid areas

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Abstract The major limitation in planning water harvesting is the lack of knowledge in the estimation of surface area and storage volume at any depth of dam reservoir. The area–volume–elevation (AVE) curve of a reservoir plays a key role in estimating the most suitable depth, optimum surface area and highest capacity of reservoir storage. The existing methods to estimate the AVE curve are costly and time-consuming and require laborious work. This study attempts to develop a method to optimize the AVE curve for earth dams, using the digital elevation model generated by the Shuttle Radar Topography Mission (SRTM) data, and integrate it with the geographic information system (GIS), known as the GIS–SRTM. The proposed method was tested using field data in the Western Desert of Iraq, which is an arid environment. Three constructed small earth dams were selected for this study. The AVE curves were extracted for Horan 2 (H2), Al-gara 2 (G2) and Al-gara 4 (G4) earth dams. Comprehensive analyses have been carried out to evaluate the performance of the AVE curves using the proposed GIS–SRTM method and the field data. From the comparison, the proposed GIS–SRTM method was able to produce reliable AVE curves with a relative error less than 20%. Additionally, the proposed method was less time-consuming and the AVE curves can be visualized immediately. The proposed GIS–SRTM method is relatively supportive in analyzing spatial data to select the optimal site for rainwater harvesting and prevent excessive evaporation losses.

Keywords Area–volume–elevation curve · GIS–SRTM method · Remote sensing · Geographical information system (GIS) · Rainwater harvesting · Arid environment

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Introduction

In arid areas, civilization depends primarily on the availability of water. Water availability in these areas is mostly associated with short duration and high intensities of precipitations. However, precipitation events occur during only short periods of a year. During these short periods, the high rate of evaporation interrupts the formation of permanent streams which are important in fulfilling the environmental and social needs (Forzieri et al. 2008). The Western Desert of Iraq is one of the regions which are classified as an arid region, and the precipitation varies in time and space. Therefore, an innovative and cost-effective water conservation alternative should be introduced in the region. Rainwater harvesting is a way to collect and conserve this precious natural source in order to overcome the issue of water availability, and it ensures continuous supply throughout the year.

Rainwater harvesting has been defined by many authors, but the Food and Agricultural Organization (Siegert 1994) defined it as the collection of runoff for productive use, while Linger et al. (2011) defined it as the collection and concentration of rainfall to make it available for domestic or agricultural uses in dry areas. Water harvesting in arid

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regions can store a significant amount of water and maintain the downstream flow. The availability of water in most arid areas is rarely sufficient, especially during drought periods. Knowledge and research on reservoir storage capacity are inadequate. Therefore, the planning and management of existing water resources are often inefficient (Mugabe et al. 2003). Quantifying the available water in these reservoirs assists the planners in satisfying the consumers' demand.

Before a rainwater harvesting structure is constructed, the optimal height of a dam should be established to maintain excellent storage characteristics. The shape of the reservoir naturally has an impact on the evaporation process, where a narrow deep reservoir has less evaporation loss than a broad shallow reservoir (Stephens 2010). The depth of a dam has a direct effect on the reservoir's surface area and capacity (Sawunyama et al. 2006). For practical aspects, obtaining this relationship is important in order to ensure sustainable water withdrawal rates or to evaluate the sedimentation rate (Haghiabi et al. 2013). In addition, the variation in storage capacity or valuation of the existing volume is essential for the management of the reservoir (Cross and Moore 2014). Therefore, the AVE curve is important for water resources modeling, planning, and management. The available methods for estimating the AVE curve include direct (reservoir survey) and indirect methods (use of topographical maps). Commonly, a field survey is done to estimate surface areas and storage capacity. However, this exercise requires tremendous labor and is very time-consuming. Hence, the assessment of reservoir capacity to the water spread area at different elevations for the reservoir with appreciable costs is crucial, especially for developing countries.

Proper water resources planning and management are becoming increasingly essential particularly in developing nations. GIS is the key tool in using, interpreting and transforming the spatial data. These functionalities will support the analysis of spatial data and hence assist the decision-making process. Many studies have employed GIS in developing, planning and managing of water resources, depending on several criteria (Tsihrintzis et al. 1996; Vorhauer and Hamlett 1996; Durga Rao and Bhaumik 2003; Jha et al. 2007; Al-Adamat 2008; Mwenge Kahinda et al. 2008; Ni-Bin and Parvathinathan 2008; Chowdary et al. 2009; Jasrotia et al. 2009; Al-Adamat et al. 2010; Jha et al. 2014). The mass curve is one of the techniques used to calculate the storage capacity of a water harvesting structure using GIS. Many previous studies on the storage capacity of rainwater harvesting structures using GIS are reported in the literature (Gupta et al. 1997; Sawunyama et al. 2006; Sattari et al. 2008; İrvem 2011; Cvar 2014; Zhang et al. 2014; Sayl et al. 2016).

The emergence of the newly available global geospatial data and integration with GIS was utilized effectively to delineate and select potential zones of a rainwater harvesting structure. The conventional planning process may not be suitable for finding a reasonable solution; therefore, discovering new alternative is necessary, especially in developing countries. The area–volume–elevation (AVE) curve of a reservoir plays a key role in estimating the most suitable depth, highest capacity and optimum surface area of reservoir. Existing methods to estimate the AVE curve are costly and time-consuming and require laborious work. The GIS can be used to determine the storage and to quantify the changes in the volume of the reservoirs.

The study focused on the use of GIS to manage and utilize the geospatial data. These geospatial data as well as hydrological and survey data, coupled with GIS, are the most powerful and cost-effective method for rainwater harvesting planning in arid regions. This study is intended to establish the area–volume–depth relationships using the digital elevation model generated from SRTM data, which were integrated with GIS. These relationships are very important for planners and can assist water management in these regions.

Study area and data

The Western Desert in Iraq is chosen as the study area. The study area covers the west and south regions of the Euphrates River as shown in Fig. 1. Many earth dams are constructed here for the provision of water. However, some of them failed to equalize water distribution throughout the year and to diminish water scarcity during the dry season. Since the catchment is located in a developing country, the data availability is rare, and its quality is low. Therefore, the use of the DEM generated by using SRTM data and GIS to estimate the AVE curve is highly needed.

This study area experienced an arid climate. Thus, summers are dry while winters are cool. These conditions caused negative impacts on the replenishing of the groundwater. The temperature monthly records differ significantly over the year; for example, the highest average monthly record in July and August is 42.8 °C while the lowest is from December to February 2.6 °C. Due to the high radiation of the sun, the land surface is very hot during the day and cold at night. Around 90% of the mean annual runoff over the catchments occurs during the period of November to April. The total annual precipitation is low, i.e., between 100 and 130 mm, and about 49.5% of the time occurs in winter, 36.3% in spring and 14.2% in the fall. The study area is characterized by a high mean annual potential evaporation which is ranging from 3000 to

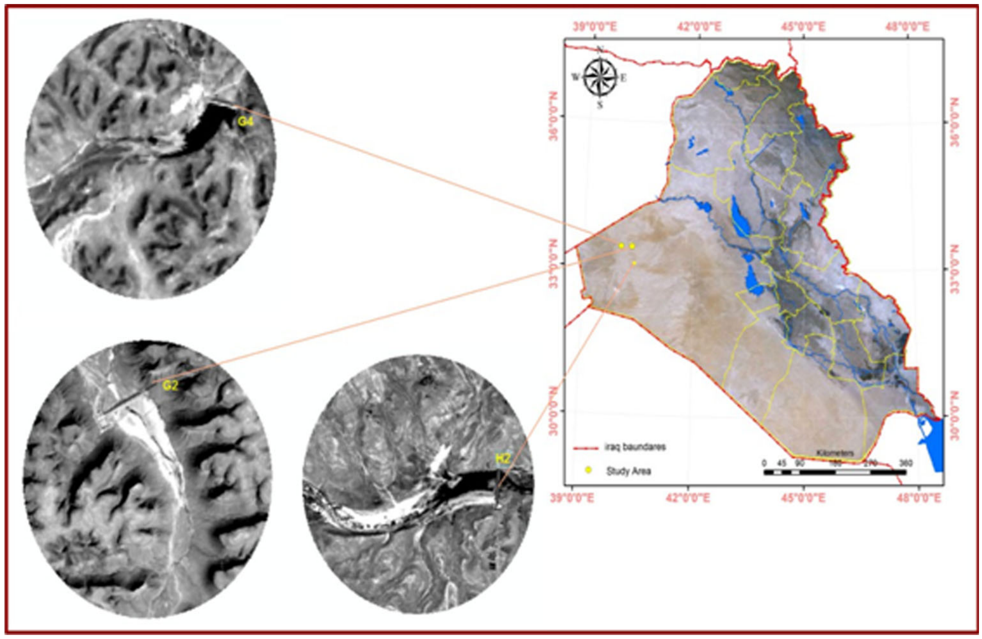

Fig. 1 Location map of study area

3500 mm. It should be noted that this catchment has significant evaporation rates, i.e., about thirty times higher as compared to precipitation. Additionally, the average monthly potential evaporation varies seasonally. The average annual of relative humidity is 46.2% and varies significantly from month to month. The wet season is normally from November to April. The highest relative humidity is usually recorded in December at 76%, while the lowest is at 21% in July. The meteorological characteristics, such as mean annual values of rainfall, evaporation, air temperature, radiation, relative humidity and speed of winds collected from five gauging stations located throughout the catchment of the study area, namely Al-Ramadi, Haditha, Al-Kaim, Al-Rutba and Al-Nukhaib during the period between 1941 and 2013, are shown in Table 1 and Fig. 2.

The details of data utilized in this study are:-

1. Survey data, collected from General Commission of Dams, Iraq, were used to produce the maps of AVE curve for rainfall harvesting structures, e.g., several small dams, namely Horan 2 (H2), Al-Gara 2 (G2) and Al-Gara 4 (G4). These maps were generated using the prismatic calculation method to compute surface area and water storage capacity. This method requires the estimation of partial volumes of the water between two contours, using the average contour area. The contour maps were extracted from the field survey using the grid method (10 m by 10 m). SRTM data were collected in February 2000, and the DEM was generated with a resolution of 30 m. Subsequently, the DEM data were rectified by ground control points.

Table 1 Mean monthly climatologically features of the case study area (Iraqi Public Authority for meteorological and seismic monitoring)

Months	Temperature (°C)	Rainfall (mm)	Wind speed (m/s)	Radiation (MJ/m^2/day)	Relative humidity (%)	Evaporation (mm)
January	7.6	26.1	2.4	232.2	69.8	78.3
February	9.5	20.4	3.1	312.5	62.7	109.4
March	13.4	15.2	3.2	405.9	54.9	171.9
April	19.5	11.4	3.1	492.1	43.3	247.1
May	24.8	6.5	2.9	583.3	34.8	336.58
June	30.2	0.1	3.0	634.3	29.5	415.12
July	33.7	0.2	3.4	636.2	28	498.75
August	32.9	0.1	2.7	594.1	28.7	449.91
September	28.1	0.6	2.0	506.0	31.9	327.2
October	22.2	14.9	2.0	393.5	43.7	222.9
November	14.3	16.4	1.8	286.8	56.5	161.1
December	9.4	27.3	2.0	217.2	69.2	82.8

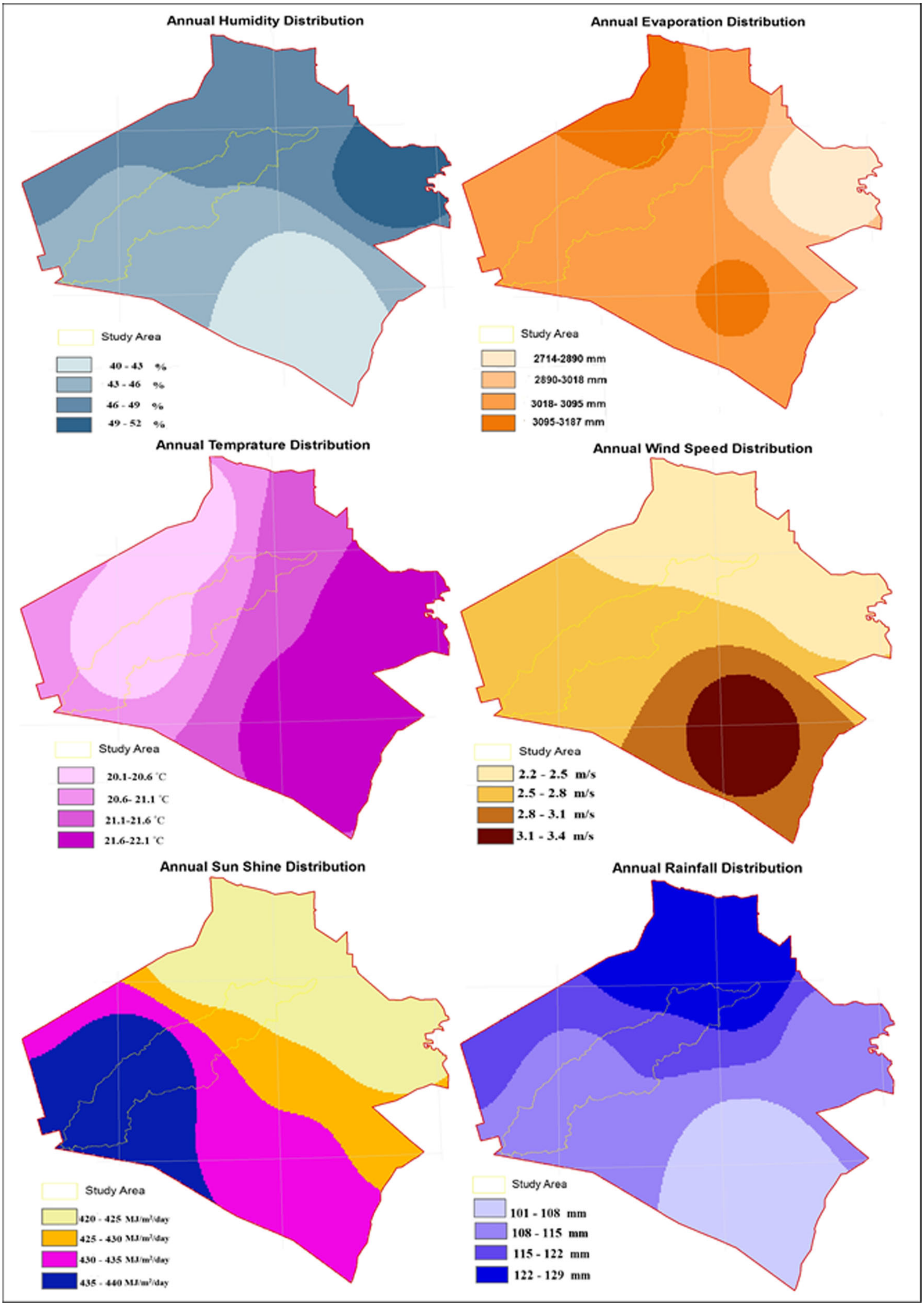

Fig. 2 Climate characteristics of the study area

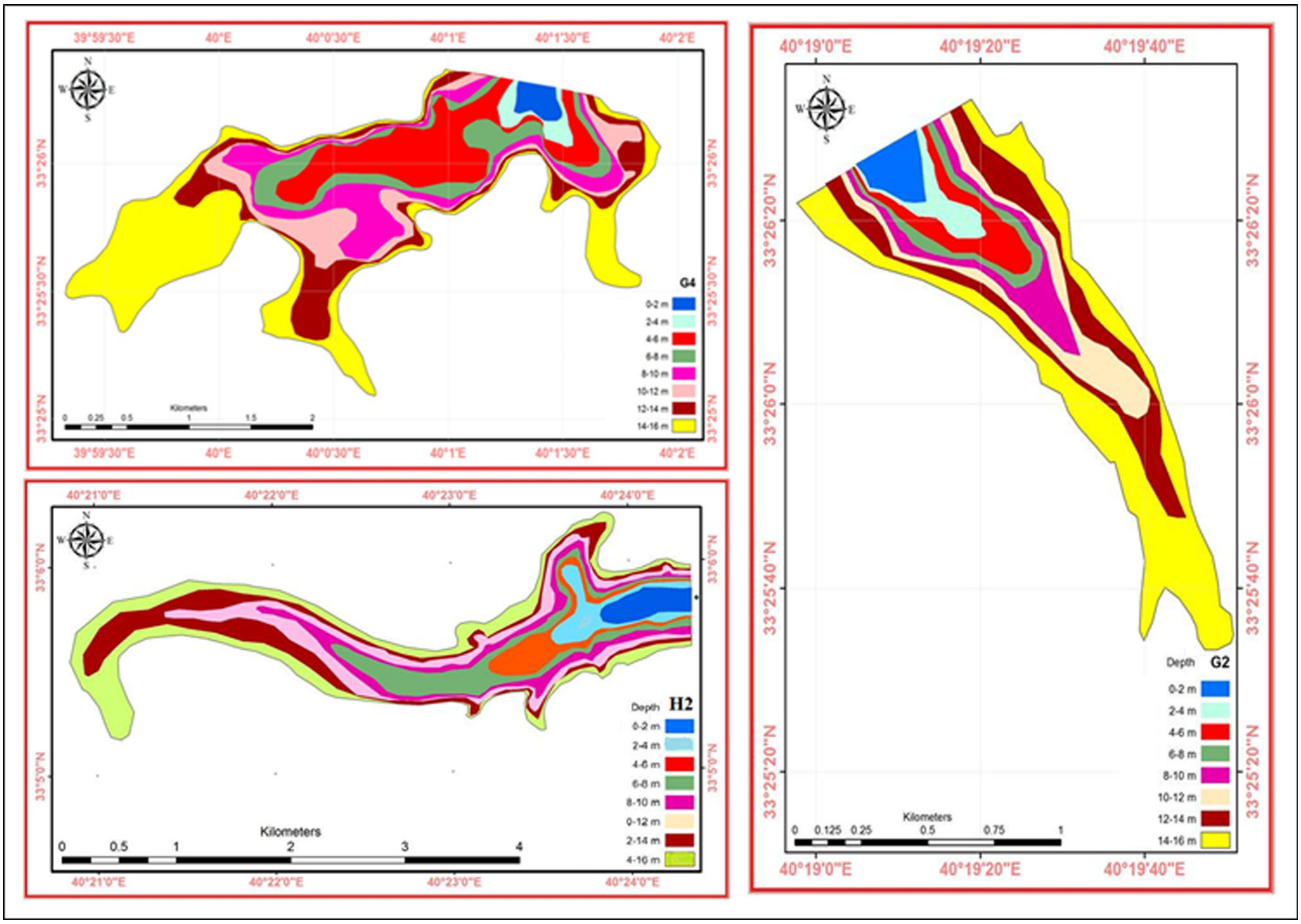

Fig. 3 Thematic maps of water level at different depths for the established dams (H2, G2 and G4)

2. Landsat satellite image 2013 was collected in March and August. These data were rectified using ERDAS Imagine software. Later, the Landsat data were analyzed using ArcGIS.

Methodology

The optimal depth of the crest was first established as this depth maintains the highest capacity of reservoir storage with the most optimum surface area, which is important especially in the arid environment because this area has a high evaporation rate. Therefore, minimizing the evaporation process, especially in a rainwater harvesting structure, is important to ensure more water can be stored. This component is highly significant, especially in an arid area where water availability is very limited.

The methodology consists of several steps. Firstly, after data preparation and generation of the DEM from SRTM, the AVE curve was developed using ArcGIS version 9.3 with Spatial Analyst. Different layers are shown in the final thematic maps which represent water levels at different depths, as shown in Fig. 3. The validation process of survey data is done by measuring the performance of each result and comparing them. Secondly, the area and volume of the three dams were examined, depending on the relative error between the survey and GIS data. Additionally, the coefficient of correlation (R^2) is used to examine the correlation between area and volume estimated using GIS and survey data. The final step is the matching of the delineated surface areas for water bodies that were extracted from the Landsat image with the surface areas which were developed by the GIS–SRTM method. Basically, GIS allows the user to visually correlate the surface area on a map. In this study, the satellite images were taken for H2, G2 and G4 during two different seasons, i.e., the rainy season (March) and dry season (August) in order to examine and make comparisons with various water storages.

Results and discussion

Meteorological factors such as relative humidity, precipitation pattern, radiation, velocity of wind and temperature have a significant influence on the evaporation rate. Since

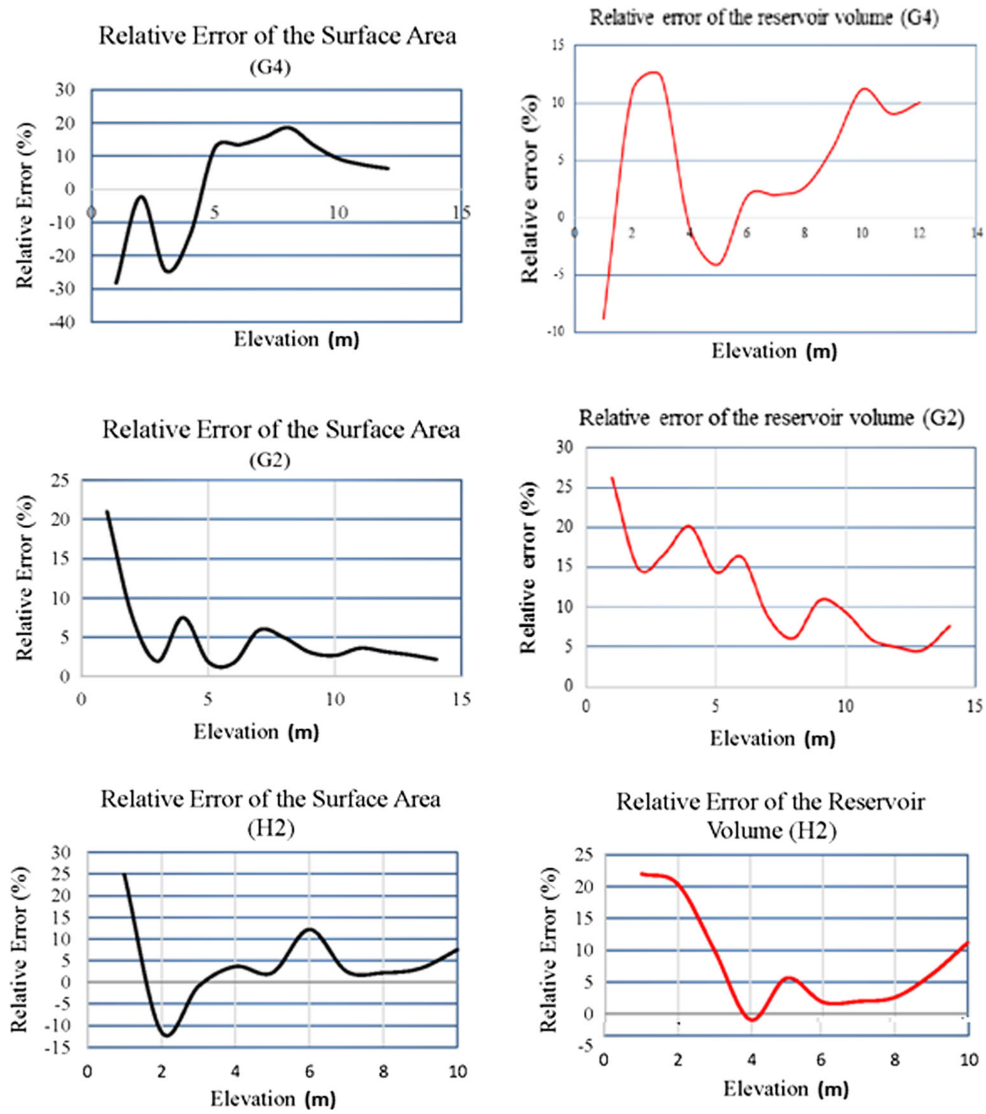

Fig. 4 Relative error for area and volume in different elevations for the established dams (H2, G2 and G4)

these factors distribute equally with only slight differences throughout of the study area, they had a similar effect on the evaporation rate. Figure 2 shows the distributions of these meteorological factors for the study area. Thus, water surface area and water depth were the parameters presented in this study.

The AVE curve was developed by utilizing the integration of geospatial data with GIS application. The AVE curves were established using the GIS–SRTM data and later compared with the data from site surveys. The results were supported by the relative error, as shown in Fig. 4. It was found that the relative error distribution is less than 20% of reservoir capacity and surface area. However, a high error percentage was observed at the initial four meters of elevation. There are two main sources of error because of the rugged terrain in some parts of the study area. It is known that the SRTM data are highly influenced by topography and therefore it causes some error in the measurement. The error may also occur during primary data acquisition and processing of the DEM which is related to a particular terrain and land cover. Also, it might be due to the difficulty of determining the datum level (lower point of storage) of the AVE curve for the proposed method. In general, the relative error of statistical indicators shows a remarkable agreement.

The regression of storage capacity–area relationship was developed using basic logarithmic theory. As shown in Fig. 5, the regression analysis for every reservoir shows an excellent value of the coefficient of determination R^2. Additionally, the analysis of R^2 indicates that the small reservoir storage capacities vary above 99 and 93% using survey and GIS data, respectively, due to their surface areas. The difference in the regression between survey data and GIS data is due to using the best fit AVE curve maps as a base of survey data. In spite of the variation in regression, it presents a relatively strong relationship between the

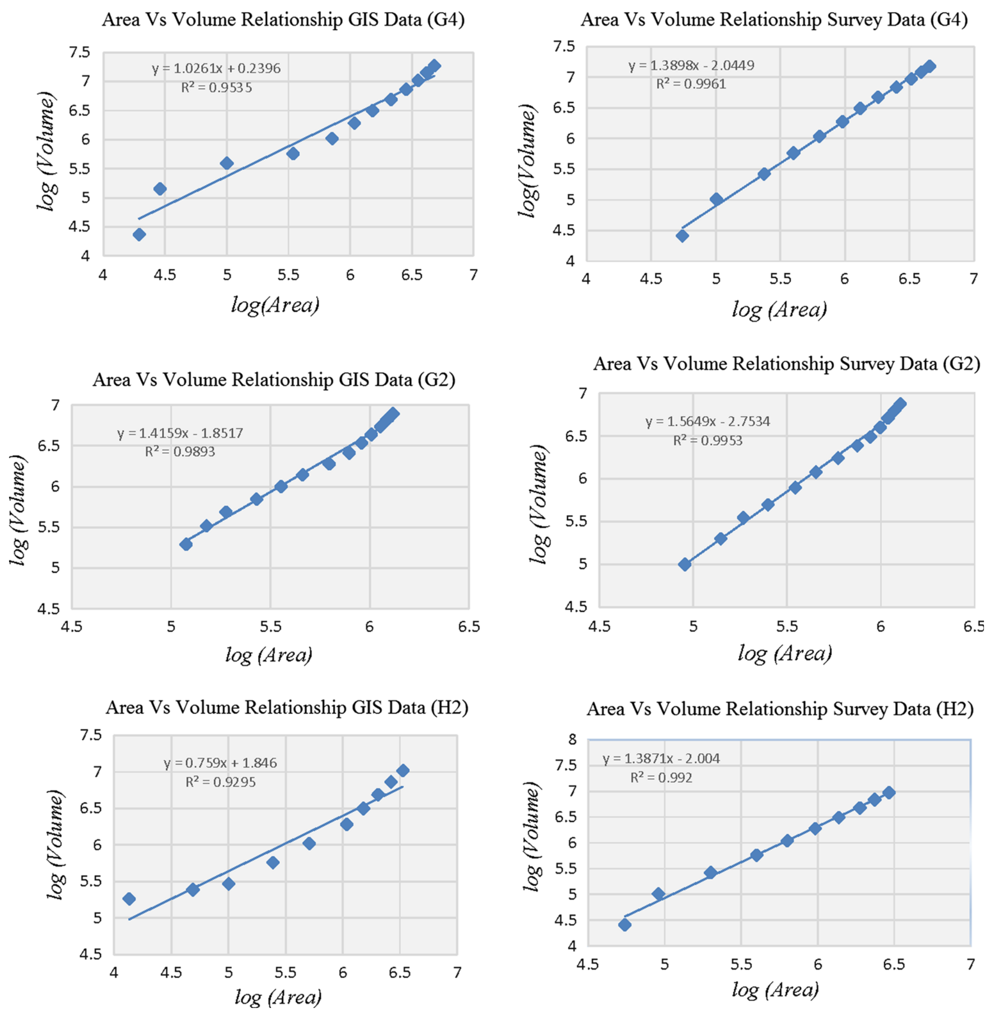

Fig. 5 Relationship between surface area and volume capacity for GIS and situ survey data for the three dams

storage capacities and the surface area for the studied reservoirs. Thus, surface areas have a strong influence on the change of reservoirs storage capacities, while the change of height has minimal effect on it. In other words, the strong relationship between area and volume can reduce the variation of the primary depth of water for each level for the studied reservoirs.

As the shape of the reservoir naturally has an impact on the evaporation process, both depth of water and surface area were considered in this study. An assumption was made in order to estimate the capacity of a reservoir; that is, it can be represented by the volume of a pyramid (Sawunyama et al. 2006). Therefore, the shape index represents the average proportion of the storage capacity of the surface area at any level of the reservoir. This feature is very important in building a rainwater harvesting structure in an arid region because it is an indicator for the shape of the reservoir, and able to decrease the evaporation rate as the surface area water is minimized. As mentioned in the previous paragraph, there is a difficulty in determining the datum level for the reservoir and the higher error occurs due to the rugged terrain. Therefore, the analysis does not include the first two meters of water elevation to minimize the average proportion indices error. Three dams, namely H2, G2 and G4, have a shape index of 2.72 (2.55), 2.57 (2.36) and 2.46 (2.49) m for the GIS (survey). The GIS application resulted in a higher shape index as compared to the survey, due to the rugged terrain in some parts of the study area. The maximum difference between the proposed method and on site survey was less than 21 cm. The error is relatively small, and this indicates that the AVE curve produced in this study has a high level of accuracy. Additionally, the shape index for small dams converges, which show that the storage capacities vary with strong and minimal influence from areas and height, respectively.

The advancement in infrared and the visible part of the spectrum technology of imagery enables researchers to use it as a tool in detecting and delineating the surface area of water bodies. Figure 6 represents the agreement between delineation of surface areas of water bodies developed from Landsat 8 images taken in 2013 compared with results from GIS–SRTM at a certain level for rainy (March) and drought

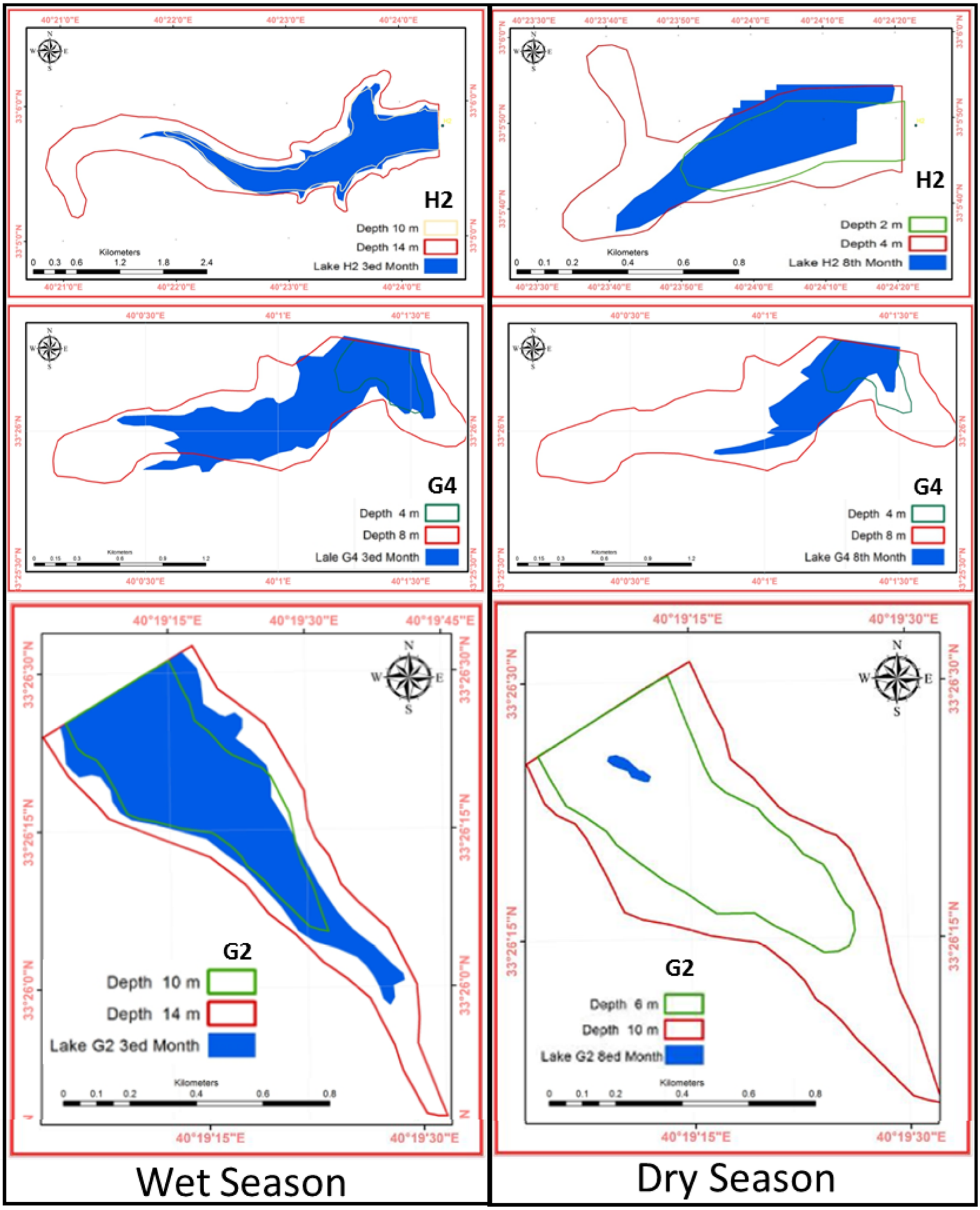

Fig. 6 Matching between the delineation of open surface area water bodies and surface area, developed by the GIS-SRTM method for rainy and drought seasons for (H2, G2 and G4) dams

seasons (August). It was found that these dams, namely H2, G2 and G4, could not offer an equalized water distribution in the drought season because the water depth is very small. In addition, it is noticeable that the outlines of the surface area for the water bodies are bounded by two successive outlines that have been created by the proposed method. This matching process is necessary to validate the proposed method of AVE extraction. The indicators for the delineation of the open surface area show a remarkable agreement with the method of extracting the AVE curve, especially when the reservoirs were full, while less accuracy was recorded when the reservoirs were empty. This may be due to the error in pixel counting when some areas covered with water were considered as a vegetation, as reported by Crapper (1980). He found that in the Landsat imagery, there is a mixed spectral signature in the perimeter cells which complicates the estimation of areas by pixels. During classification, floating vegetation in shallow water may be categorized as wetlands and submerged aquatic vegetation is classified as water. The coarse grid, i.e., 30 m used in this study may also contribute to the inaccuracy. Additionally, several other factors that contribute to higher error are the changing reservoir shape due to the sedimentation, initial data acquisition and processing of the DEM, especially on rugged terrain and land cover type.

Conclusion

Reservoir storage information plays an important role in dam site selection. Geospatial data are a necessity in water resources management, for instance in the estimation of storage capacity for the reservoir, especially for developing countries. The main objective of this study is to propose a method known as GIS–SRTM to generate the AVE curve in the Western Desert of Iraq. The AVE curve is one of the tools in the decision-making process concerning rainwater harvesting location. According to the preceding application analysis, the proposed approach can efficiently produce reliable AVE curves. From the finding, it is highly recommended that the proposed GIS–SRTM method be adopted for catchments that have less variation in ground elevation. Furthermore, for any site selection, the shape index must be taken into consideration. The process of producing the AVE curves using GIS is considerably less time-consuming, and results can be visualized immediately. The GIS–SRTM approach is relatively accurate in analyzing spatial data, and the results can be used in selecting the most suitable site for rainwater harvesting, where excessive evaporation losses are minimized.

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