A GIS-based approach for identifying potential sites for harvesting rainwater in the Western Desert of Iraq

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Abstract
People living in arid and semi-arid areas with highly variable rainfall and unforeseeable periods of droughts or floods are severely affected by water shortages and often have insecure livelihoods. The construction of dams in wadis to harvest rainwater from small watersheds and to induce artificial groundwater recharge is one of the solutions available to overcome water shortages in the Western Desert of Iraq. The success of rainwater harvesting (RWH) systems depends heavily on their technical design and on the identification of suitable sites. Our main goal was to identify suitable sites for dams using a suitability model created with ModelBuilder in ArcGIS 10.2. The model combined various biophysical factors: slope, runoff depth, land use, soil texture, and stream order. The suitability map should be useful to hydrologists, decision-makers, and planners for quickly identifying areas with the highest potential for harvesting rainwater. The implementation of this method should also support any policy shifts towards the widespread adoption of RWH.

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1. Introduction

Until the 1970s, Iraq was commonly considered to have rich water resources due to the Tigris and Euphrates Rivers. The construction of dams in these rivers and their tributaries outside the Iraq border, together with the effects of global climate change and the mismanagement of water resources, however, have caused water shortages in Iraq. The growing demand for water in Turkey and Syria could lead to the drying of the Tigris and Euphrates Rivers by 2040 (Al-Ansari, Abdellatif, Ali, & Knutsson, 2014). People living in arid areas with highly variable rainfall and unforeseeable periods of droughts or floods, such as Iraq’s western desert, are the most affected by climate and scarcity of water and often have insecure livelihoods. The use of non-conventional water resources, e.g. rainwater harvesting (RWH), can overcome the water shortages in Iraq. The database of the World Overview of Conservation Approaches and Technologies (Mekdaschi Studer & Liniger, 2013) defined RWH as: “The collection and management of floodwater or rainwater runoff to increase water availability for domestic and agricultural use as well as ecosystem sustenance”. The main role of RWH is to increase the amount of available water by capturing rainwater in one area for local use or for transfer to another area. RWH has been used in Iraq for > 5000 years (Ben Mechlia & Ouessar, 2004). The construction of dams on wadis in recent decades to harvest water from small watersheds and for inducing artificial groundwater recharge has become an acceptable practice in these regions (Abdulla, Amayreh, & Hossain, 2002). The success of RWH systems depends heavily on their technical design and the identification of suitable sites (Adham, Riksen, Ouessar, Abed, & Ritsema, 2017; Al-Adamat et al., 2012). More than the financial terms and economic benefits are now considered. Populational and environmental aspects play major roles. Properly planning, designing, and implementing dam construction would improve the availability of rainwater for domestic
Various methodologies have been developed for the selection of suitable sites and techniques for RWH (Ahmad, 2013). Field surveys are the most common method for small areas. The identification of appropriate sites for the various RWH technologies in large areas is a great challenge (Prinz, Oweis, & Oberle, 1998). Sen and Al-Subai (2002) identified and evaluated the factors that could affect dam location in catchments and hence the planning of water resources of proposed reservoirs. These authors studied the effects of sedimentation and flooding on dam location and construction in Saudi Arabia. Forzieri, Gardenti, Caparrini, and Castelli (2008) presented a methodology for assessing the suitability of sites for dams. The selection criteria were defined both qualitatively and quantitatively and were based on a territorial analysis using satellite data in combination with hydrological and climatological information. The methodology is particularly useful in areas where very little territorial information is available, such as most developing countries, and has been applied in the region of Kidal in Mali, where 66 sites were assessed, of which only 17 satisfied the proposed selection criteria. The authors selected suitable construction sites from prevalent engineering and technical perspectives and neglected others such as sociopolitical perspectives (Forzieri et al., 2008). Weerasinghe, Schneider, and Loew (2011) focused on using a geographic information system (GIS) and remote sensing (RS). They developed an integrated methodology for assessing water management. The model accordingly specifies potential water-harvesting and storage sites for water storage and soil-moisture conservation on farms (Weerasinghe et al., 2011). Ammar, Riksen, Ouessar, and Ritsema (2016) reviewed the methodologies and the main criteria that have been applied in arid and semi-arid regions (ASARs) during the last three decades. They categorised and compared four main methodologies of site selection, identified three main sets of criteria for selecting RWH locations, and identified the main characteristics of the most common RWH techniques used in ASARs. The methods were diverse, ranging from those based only on biophysical criteria to more integrated approaches, including the use of socioeconomic criteria, especially after 2000. Most studies now select RWH sites using GISs in combination with hydrological models and/or multi-criteria analysis (MCA).

The identification of suitable sites for RWH is an important step towards maximising water availability and land productivity in ASARs. Integrated studies of runoff modelling, GISs, and RS have successfully targeted sites suitable for RWH (Adham, Riksen, Ouessar, & Ritsema, 2016a, 2016b; De Winnaar, Jewitt, & Horan, 2007; Padmavathy, Ganesha Raj, Yogarajan, Thangavel, & Chandrasekar, 1993). GISs and RS can meet the challenges of missing data required for the selection of potential sites for RWH, especially in ASARs.

The main objective of the present study was to identify suitable sites and the number of dams required to harvest rainwater in an arid region (wadi Horan, Western desert of Iraq) by integrating runoff modelling and a GIS.

2. Materials and methods

2.1. Study area

Wadi Horan is in the western part of Iraq in Al-Anbar province, about 450 km west of the capital Baghdad (Fig. 1). The catchment has an area of 13 370 km² and an arid climate with dry summers and cool winters. The mean annual rainfall is very low (75–150 mm). About 49% of the rain falls in winter, 36% in spring, 15% in autumn, and no rainfall in summer. The mean annual temperature is 21 °C, July is the hottest month, and January is the coldest month (Sayl, Muhammad, Yaseen, & El-shafee, 2016). The average annual potential evaporation is 3200 mm, and the monthly average evaporation varies strongly with season (Naba, Shazwani, Ahmed, & Dahham, 2016). The wadi is completely dry during most of the year, but short intense floods occur during the rainy season.

The main components of RWH systems in dry areas are a catchment area to collect the runoff from rainstorms and an earthen dam to form a reservoir for storing the harvested runoff for domestic and agricultural purposes. Dams are one way to store rainwater in the rainy seasons for use in the dry seasons and are effective structures for the proper use of water in Iraq.

Most of the exposed rocks in the wadi Horan are hard limestone (Alhadithi & Alaraji, 2015). They provide a good base for use and agricultural development.

Fig. 1. Location of the wadi Horan watershed.
dams or barriers and can be used to cover the front side of the barrier. The sites of the dams were selected by their drainage area and the availability of a hard, narrow cross-section of the valley with high shoulders to minimise the amount of construction material needed for building the dams, minimise evaporation losses, and ensure the required storage.

2.2. General approach

The identification of suitable sites for RWH consists of four steps:

i. Selection of appropriate criteria
ii. Classification of suitability for each criterion
iii. GIS analysis and generation of suitability maps
iv. Site identification.

2.2.1. Criteria selection

Food and Agriculture Organization (FAO) lists six key factors for the assessment of sites for soil water conservation: climate, hydrology, topography, agronomy, soils, and socioeconomics (Kahinda, Lillie, Taigbenu, Taute, & Boroto, 2008). Five of these criteria were used to identify potential sites for small dams based on a literature review, expert judgment, and most importantly, available data. We followed the recommendations of the FAO and used rainfall and runoff as parameters for climate, streamflow order as a parameter for hydrology, slope as a parameter for topography, land use/cover as a parameter for agronomy, soil texture as a parameter for soils. We did not include socioeconomic criteria.

2.2.1.1. Slope. Slope plays an important role in the generation of runoff and thus influences the amount of sedimentation, the speed of water flow, and the amount of material required to construct dams (dyke height) (Adham et al., 2016a). Critchley et al. (1991) did not recommend water harvesting for areas with slopes $\geq 5\%$, because they are susceptible to high erosion rates due to irregular runoff distribution and because large earthworks are required (Al-Adamat, Diabat, & Shatnawi, 2010). A digital elevation model (DEM) with 30-m resolution was used to generate a slope map (Fig. 2a). Sinks and flat areas were removed using ArcGIS 10.2 to
maintain the continuity of water flow to the catchment outlet. The slopes were then reclassified to generate the map (Fig. 2b).

2.2.1.2. Runoff depth. Runoff depth is an important criterion for selecting suitable sites of RWH. Runoff depth is used to assess the potential water supply during runoff. The curve number (CN) provided by the Soil Conservation Service was used to estimate the runoff depth. CN is predictable from the effects of soil and land cover on rainfall/runoff. CN was estimated for each pixel for the study area using the land-cover and soil-texture maps. Runoff depth can be expressed as:

\[ Q = \frac{(P - I_a)^2}{(P - I_a) + S} \]

where \( Q \) is runoff depth (mm), \( P \) is precipitation (mm), S is potential maximum retention after the onset of runoff (mm), and \( I_a \) is an initial abstraction (mm) that includes all losses before the onset of runoff, infiltration, evaporation, and water interception by vegetation. \( I_a = 0.2S \) determined by analysing the rainfall data for many small agricultural basins (Melesse & Shih, 2002). Eq. (1–3) can therefore be expressed as:

\[ Q = \frac{(P - 0.25S)^2}{(P + 0.8S)} \]

\[ S = \frac{25400}{CN} \]

where \( S \) can be calculated using CN as:


2.2.1.3. Land cover/use. Land cover is correlated with the runoff produced for each rain in a given area. For example, denser vegetation is correlated with higher rates of interception and infiltration and thus lower runoff (Kahinda et al., 2008). Land cover was obtained from satellite imagery (Landsat 8–2013) with a spatial resolution of 30 m. A maximum-likelihood algorithm was used to classify land cover using the means, variances, and covariances from the signature. Four types of land cover were identified: bare soil, urban areas, water and moist soil, and farmland and grass (Fig. 2d).

2.2.1.4. Soil texture. Soil texture affects both the rate of infiltration and the surface runoff. The textural class of a soil is determined by the percentages of sand, silt, and clay. White (1987) indicated that fine- and medium-textured soils were generally more desirable for RWH because of their higher retention of water. Soils with high water-holding capacities are more suitable for RWH (Adham et al., 2016a). Sites with clay soil are the best for water storage due to the low permeability of clay and its ability to hold the harvested water (Mbnilinyi, Tumbo, Mahoo, & Mkiramwinyi, 2007). Soil texture will therefore likely be a critical criterion for selecting a site for a RWH scheme, especially if the purpose is to preserve the water for human, livestock, and agricultural purposes (Al-Adamat, 2008). Fig. 2e shows the variety of soil texture based on clay content.

2.2.1.5. Stream order. The wadis in the wadi Horan watershed are the main sources of surface water. The water collected during the winter is used for human needs, watering livestock, and other agricultural purposes (Al-Adamat, 2008). The suitability of RWH (dams) depends on wadi density, with highly dense areas the most suitable. Stream order is based on the connection of tributaries. The order of a stream denotes the hierarchical connection amongst stream segments and permits the categorisation of drainage basins by their size. The analysis of stream order for mapping RWH is important, because lower stream orders have higher permeability and infiltration and vice versa. Moreover, dendritic drainage patterns due to the linking of streams have homogeneous soil texture and a lack of structural control. The map of stream order is presented in Fig. 2f, where potential RWH sites are classified as very low ( \(< 4\) ), low (5), moderate (6), high (7), and very high ( \(> 7\) ).

2.2.2. Classification of suitability for each criterion

Each criterion was first classified due to the variety of measurements and scales for the various criteria. The parameters listed in Table 1 were used to classify pixel values from 0 to 10. The scores reported in Table 1 were discussed and adjusted together with technical experts. The most suitable areas were classified as 10, and the least suitable were classified as 0.

Scaled maps were produced for each criterion with pixel values ranging from 0 to 10. An integrated suitability map was produced by combining criterion layers using a raster calculator. Suitability values were then classified into five classes: very high suitability, high suitability, medium suitability, low suitability, and very low suitability. Table 1 shows the assigned scores based on discussions and consultations with experts and on published information.

2.2.3. GIS analysis and generation of suitability maps

The GIS database required for identifying potential sites for RWH was developed using ArcGIS with both vector and raster databases. A suitability model was developed using ModelBuilder in ArcGIS 10.2 to implement all processes for identifying sites suitable for RWH (Fig. 3).

Areas suitable for dams were identified by reclassifying layers of biophysical criteria and combining them using the raster calculator tool in the spatial analyst module of ArcGIS 10.2. Each criterion was clipped to the study area, reclassified to numeric values, and assigned suitability rankings for dams based on Table 1.
2.2.4. Site identification

The most suitable sites for dams were identified by the visual interpretation of satellite images and analyses of large-scale cartography. The selected sites were then assessed by the other criteria to identify the best sites for RWH (dams). A suitable site for a dam is “a place where a wide valley with high walls leads to a narrow canyon with tenacious walls” (Sайл et al., 2016). Such sites minimise dam dimensions and costs, but steep valley slopes should be given a low priority, because dams at such sites are rarely economical. Narrow valleys are best identified from shuttle

Fig. 3. Flow chart for the identification of potential RWH sites.

Fig. 4. Suitability map for the identification of potential dams.
Study area with three potential dams locations. Cross-sections of the three sites in the upstream (No. 31), central (No. 22), and downstream (No. 13) areas of the watershed (left), and the generated thematic maps for each of three dams that represent the water level at different depths (right).

Fig. 5.
radar topography mission (SRTM) data and satellite images (Quickbird satellite images). Valley width is best estimated by visual interpretation elaborated by SRTM in GIS (global mapper 10).

3. Results and discussion

The first step in the methodology is to prepare all data for the main criteria. The DEM with 30-m resolution was clipped and extracted. From this DEM the slopes of the watershed were extracted. The spatial analysis of the main criteria is shown in Fig. 2. Slope and runoff were correlated: runoff increased with slope (Fig. 2b,c). Slopes were clearly steeper in the mountainous area (upstream) and along the main wadi. Runoff depth increased towards the downstream area of the watershed. Four land use classes were distinguished, with bare soil covering more than 70% of the watershed. Urban areas and water bodies occupied only a small percentage of the area (Fig. 2d).

The five main layers were integrated, but each pixel had a different score based on Table 1, when reading them into ModelBuilder in ArcGIS 10.2. The suitability model generated a map with five classes of RWH suitability: very high suitability, high suitability, medium suitability, low suitability, and very low suitability (Fig. 4).

These results show that most of the downstream area of the watershed was suitable for water harvesting. This area had steeper slopes and dense hydrological networks. The majority of the areas with very high to high suitability had slopes between 1.5% and 4.5% and were intensively cultivated. The main soil texture in the areas with very high and high suitability were clay and silty clay, and the runoff depth varied between 70 and 90 mm. Runoff depth and slope were the main criteria for identifying areas as ones with low and very low RWH suitability. These results are in agreement with those of Mbilinyi, Tumbo, Mahoo, Senkondo, and Hatibu (2005), who indicated that areas having gentle to moderate slopes combined with soils which have a high water-holding capacity, such as clay and silty clay, were suitable for constructing RWH structures.

Dams were the most common and suitable RWH structure in this catchment and have been used for a long time. The main characteristic of the dams was that they were in the main wadi stream. The application of our five layers and the multi-criterion option of ArcGIS yielded the suitable locations for these dams (Fig. 4). Potential dam locations were chosen based on estimates of the available runoff that could be stored behind the dams. We identified 39 potential sites that were compatible with the suitable areas identified in the first step (Fig. 4) based on the visual interpretation of satellite images and an analysis of large-scale cartography. To assist planners in analysing the match between water supply and water demand, the reservoir capacities must be known to quantify the available water volume at any level. Each potential dam site was further analysed by calculating characteristics such as storage area, required length, and height of the dam. Examples of cross-sections are shown in Fig. 5 (left) for three sites: one in the upstream area (No. 31), the central area (No. 22) and the downstream are (No. 13) of the watershed. The volumes and heights of the dams were calculated from a triangulated irregular network using the tools of ArcGIS. The final thematic maps showed different layers, representing water level at different depths shown in Fig. 5 (right). This figure shows the surface area for the three reservoirs. Evaporation losses might be extremely high and will increase with an increasing surface area of the stored water. Therefore, the optimal dam heights with maximum storage of water and minimum surface area of reservoir are required especially in arid regions with high evaporation losses. In addition, the capacity of the reservoir that can be estimated by computing the surface area and reservoir depth at any level is a vital concern in reservoir operation and management.

To show the relationship between dam height and storage capacity, we considered the three locations presented in Fig. 5 again. From the area of the reservoir and the depth of water at each point the storage of water was computed (assuming the water level reaches the top of the dam). These results are presented in Fig. 6 It can be seen there is a nearly linear relationship between storage capacity and dam height for dam 13. This is in agreement with the results shown in Fig. 5 where each additional meter in dam height causes about the same increase in storage area. The data for dam 22 show hardly any storage difference until the dam is 7 m high. If the height exceeds 7 m, a large area will be flooded and storage capacity will increase. This increase is even stronger for dam 31.
when it exceeds 8 m. These data are presented as an illustration of the method only, because these dam heights may not be feasible in practice (movement of material, width of dam, cost of labour, etc.).

The success of an intervention depends not only on technical aspects, as in this study, but also on how well it fits within the stakeholder’s social context and the economic benefit it provides him/her. Several socioeconomic criteria can have an influence, such as ownership, distance to settlements/roads, family size, and education, but identifying good indicators associated with the functioning of these RWH systems is much more difficult for socioeconomic than for biophysical conditions. The inclusion of socioeconomic criteria is thus very important for obtaining meaningful information for improving the effectiveness of current RWH systems and for planning future structures.

4. Conclusion

Potential RWH sites were identified using a GIS-based suitability model, created with ModelBuilder in ArcGIS 10.2. The suitability model combined biophysical factors: slope, runoff depth, land use, soil texture, and stream order. The present study found that ArcGIS was a very useful tool for integrating diverse information to find suitable sites for dams for harvesting rainwater. ArcGIS was a flexible, time-saving, and cost-effective tool for screening large areas for their suitability of RWH intervention. The suitability map will be useful to hydrologists, decision-makers, and planners for quickly determining areas that have RWH potential. Map quality depended on the quality and accuracy of the data, including how the data were gathered, processed, and produced. High-quality data provided the most reliable and efficient output.

Socioeconomic criteria, however, can also be important for water harvesting. Social and economic factors should be studied in more detail and seriously taken into account. Fieldwork should be carried out on the selected sites to ensure that they do not conflict with other land uses in the area that the available GIS data do not identify. The analysis as presented, however, provides first a valuable screening of large areas and can easily be modified to incorporate other criteria or information with other spatial resolutions.

References


