Potential Sites for Hill Reservoirs: An Assessment Methodology Using GIS and Remote Sensing Tools

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Abstract

This study investigates the development of a methodology to identify potential sites for hill reservoirs using remote sensing and GIS, in an 1113-km^2 area in northeast Tunisia. The general approach has two steps; first, extract the area and mean slope of each watershed of 16 hill reservoirs, and then produce a hill reservoirs suitability map of the entire study area based on these watershed physical characteristics. To determine the watershed area a representative pixel of each hill reservoir was settled and its contributing area was extracted. Moreover, a typical watershed was defined and watersheds mean-slopes were extrapolated to the entire study area.

The methodology is validated by nine additional hill reservoirs. These reservoirs lie in the suitable class for potential hill reservoirs in suitability map, which means that the methodology is appropriate to identify hill reservoirs potential sites. This methodology is simple and easily applied and extendable to similar areas in West Asia and North Africa.

Introduction

Hill reservoirs are a recent water-harvesting system in Tunisia. Their number has been increasing rapidly during the last few years. In addition to their role in erosion control and aquifer recharge, they are used to store water during precipitation events to irrigate nearby areas during dry periods (Ben Mechlia and Ouessar, 2004), thereby contributing to the improvement of the livelihood of the people in rural areas.

The cost to build these water-harvesting systems is high, with a significant part required to cover the cost of data collection for selecting suitable sites. In general, these data are collected in hard-to-reach locations. Techniques such as remote sensing could be very useful for supplying valuable information about potential sites with low cost. Incorporating this data in a geographical information system (GIS) may help develop a decision-making system for site selection at regional scales.

The aim of this paper is to present a methodology for identifying hill reservoirs potential sites in Tunisia, using a selected number, generally available, remote sensing datasets. Therefore, the methodology could be easily extended and applied to other areas of the world, especially the countries of West Asia and North Africa. This work is part of a regional project on the "Assessment of water harvesting and supplemental irrigation potential in arid and semi-arid areas of West Asia and North Africa".

Materials and Methods

Study Area

The selected study area corresponds to an ASTER scene that falls mainly in Zaghouan, Nabeul and Ben Arous districts. This area, with 1113 km^2, is located in the northeastern part of Tunisia. The climate is semi-arid. The mean annual temperature of the main city of the study area, Zaghouan, is 18ºC and the mean annual precipitation is 449 mm. The altitude is variable, with a highest point of about 1293 m above sea level (asl), corresponding to Djebel Zaghouan and a lowest point of about 50 m asl close to Oued Rmel dam. More than 20 hill reservoirs are constructed in this area.

Methodology

To build a hill reservoir in a specific site, it is important to ensure sufficient water flow to that site. The topography influences water supply, by affecting the trajectory, speed and volume of the water flow. The main parameters defining water flow processes related to topography are the contributing area and the mean slope. The contributing area is defined as the area receiving the rainfall water that can flow to the reservoir. This parameter can be given for each point by the flow accumulation value, defined as the number of grid cells whose flow paths pass through that point (Burrough and MacDonnell, 2001). Consequently points with zero flow accumulation receive no runoff. The slope is defined as the maximum rate of change from a given point to its neighbors. The watershed mean slope is an important factor for selecting potential hill reservoir sites.

The general approach followed for mapping potential hill reservoirs sites was: (i) extract the physical watershed characteristics of a number of existing hill reservoirs, (ii) based on these characteristics carry out the suitability map for potential hill reservoir in the entire study area using single-objective multi-criteria analysis. Specifically, we considered that physical criteria influencing the selection of water-harvesting sites are: 1) watershed area and 2) watershed mean slope. Other criteria influencing hill reservoir site selection such as socioeconomic parameters, land cover and geology are not included in this study.

Two geometrically corrected ASTER images (12 March 2001 and 22 June 2003) and a 2001 ASTER DEM (Digital Elevation Model) were used. The 2001 ASTER image served to identify hill reservoirs. The ASTER DEM was employed to delineate the watershed of each hill reservoir, to extract its characteristics (area and slope), and to obtain the final potential hill reservoir sites map. The 2003 ASTER image served to evaluate the methodology. Thus, the steps followed to develop the methodology were: (i) identification of existing hill reservoirs, (ii) characterization of their watershed areas, (iii) determination of suitability map according to watershed area, (iv) definition of a watershed typical size, (v) determination of suitability maps according to mean watershed slope, (vi) preparation of the potential hill reservoir sites map, and (vii) evaluation of the results.

Hill reservoir identification

To identify and localize the hill reservoirs from the 2001 and 2003 ASTER images, a decision tree classifier was employed (Chuvieco, 2002), using Idrisi for windows software. Three bands of the ASTER images were used: green, red and near infrared. The red and near infrared were used to distinguish water bodies and mountain shadows from the rest of the land covers, and the green band to separate water bodies from mountain shadow. The outcome of this process is two hill reservoirs maps, one of the year 2001 and the other of 2003.

The reliability of these maps was double checked as follows:

- Visually by ensuring the presence of a dike downstream from each hill reservoir.
- With the help of a hydrographic network data-layer obtained from Tunisia's “Carte Agricole” (CRDA-Zaghouane, 2004). Each hill reservoir has to fit on this network.

Watersheds area calculation

For computation of the watershed area of each hill reservoir, the flow accumulation map was derived from the 2001-ASTER DEM using Hydrotools add-in program for Arcview 3.x (Schäuble,, 2003). Each cell stores the number of cells flowing to it (ESRI, 1999). Afterwards, each watershed area was calculated by multiplying the cell size (125 m2) with the flow accumulation cell value of the hill reservoir dike.

Typical watershed definition and mean slope calculation

The term typical watershed is used here to refer to a representative watershed of all potential hill reservoirs. This typical watershed has two main characteristics: an area and a form. Identification of these characteristics enables the estimation of the mean slopes of all potential watersheds in the study area as we will see hereafter. The form of this typical watershed was assumed square because it is the basic form of all grid maps. The size is identified following these steps:

- The watershed map of existing hill reservoirs was obtained. For this each hill reservoir was represented by one point on its dike. Then the contributing area was delineated from Aster DEM map using Hydrotools add-in program for Arcview 3.x.

- The cell resolution of the watershed map was increased progressively by aggregation of neighboring cells from 15 to 1500-m resolution cells. The outcomes of this process were 8 watershed maps with different resolutions: 15, 150, 750, 900, 1050, 1200, 1350, and 1500 m.
- For each watershed map the number of hill-reservoir watersheds represented by only one cell and the number of hill-reservoir watersheds not represented by any cell was calculated. The cell resolution of the watershed map that contained the highest number of watersheds represented by one pixel and the lowest number without representation was considered the best resolution. This resolution maximizes watershed intrinsic information and minimizes data coming from adjacent areas. The typical watershed size was assigned the cell size of this map.

Once the typical watershed size was defined, the 15-m resolution slope map was re-sampled to this typical size. Each pixel in the obtained map corresponds to the average slope of all the original 15-m pixels that made it up. To assess the resolution reduction effect on watersheds mean slopes, a linear regression was made between the watersheds mean slopes obtained from the 15-m map and the re-sampled map.

Suitability map establishment

A pixel was considered suitable for hill reservoirs if its contributing area fitted in between the minimal and the maximal watershed area of the existing hill reservoirs. A watershed area suitability map was obtained from the flow accumulation map, in which each pixel satisfying the suitability criterion coded 1 and the rest coded 0.

Secondly, a pixel was considered suitable for a hill reservoir if its value in the reduced-resolution slope map fell within the range of watersheds mean slopes of the identified hill reservoirs. A Boolean map was obtained by giving the number 1 to each suitable pixel and a number 0 to the unsuitable pixels. The suitability map according to slope was then obtained by re-sampling this Boolean map to the initial resolution (15 m).

Multi-criteria evaluation was performed combining both Boolean maps by means of an intersect operator; a site was considered suitable for hill reservoirs if it fulfils both the area and slope criteria. The result is a map which contains all potential sites for hill reservoirs.

Validation

The method was validated using additional hill reservoirs recognized on the 2003 ASTER image. These reservoir that were not identified in 2001 – they were either dry or not built yet – were overlaid by the potential sites map. The percentage of these reservoirs lying in the suitable class was calculated.

Results and Discussion

Identification of Hill Reservoirs and Watershed Area

Sixteen hill reservoirs were identified on the 2001 image and an additional nine on the 2003 image. The dike of each hill reservoir was visible on the images and all reservoirs were sited on the hydrographic network obtained from the Carte Agricole (CRDA-Zaghouane, 2004). These results indicate the applicability of the hill reservoirs identification methodology.

The smallest watershed area among these 16 hill reservoirs was 37 ha and the biggest 635 ha, with an average area of 215 ha. This range matches well with the official information of the Ministry of Agriculture and Water Resources (MAWR, 2004), which states that the watershed areas of the hill reservoirs in the districts Zaghouane, Nabeul and Ben Arous are between 40 and 700 ha.

Typical Watershed Size

The relationship between resolution and the number of watersheds represented by one pixel and zero pixels is presented in Fig. 1. This figure shows that at resolutions up to 1200 m the number of unrepresented watersheds is low (three or less). However, beyond this resolution the number of unrepresented watersheds increases exponentially; five at 1300 and ten at 1500 m. On the other hand, the number of watersheds represented by one pixel increases from one at 750-m resolution to reach a maximum of eight watersheds at 1050 m, and decreases again to three watersheds at 1500-m resolution. Therefore, 1050-m resolution, equivalent to an area of 110 ha, was the best size of the typical watershed to represent potential hill reservoirs watersheds in the study area.

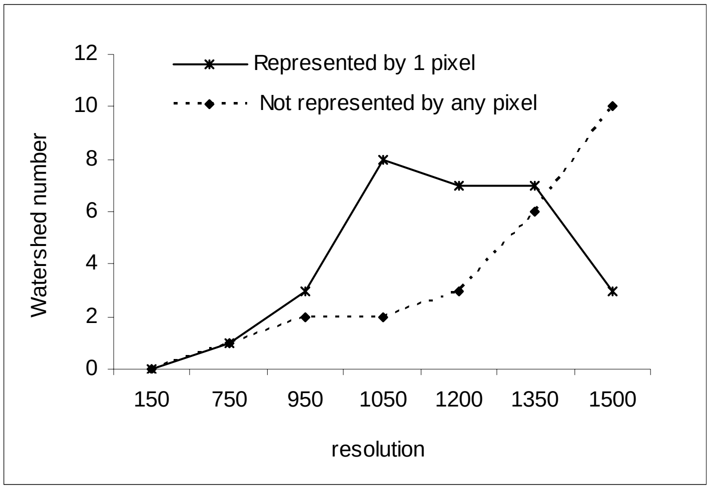

Fig. 1. Relationship between watersheds maps resolution, and the number of watersheds represented by one pixel and by no pixel.

Furthermore, the linear regression applied between the watersheds mean-slope values obtained from 1050-m resolution and from 15-m resolution map (Fig. 2) corroborates this choice ($r^2 = 0.89$ and slope = 1.03). Indeed the use of 1050-m resolution does not alter significantly the values of the watersheds' mean-slope; among the 16 analyzed watersheds 15 have almost the same mean-slope values with 1050-m resolution as with 15-m resolution. Only one watershed has a mean-slope that is quite different at the two different resolutions (39% at 1050-m versus 29% at 15-m). This difference is due to the elongated form of this watershed (Gravelius Compactness Index = 1.79).

According to these analyses, 1050-m resolution could be used to estimate the mean-slope for potential hill reservoirs watersheds in the study area. With this typical watershed size (110 ha), 14 watersheds were represented. They were composed by a total of 28 pixels with slopes ranging from a minimum of 6% to a maximum of 40% and an average of 21%.

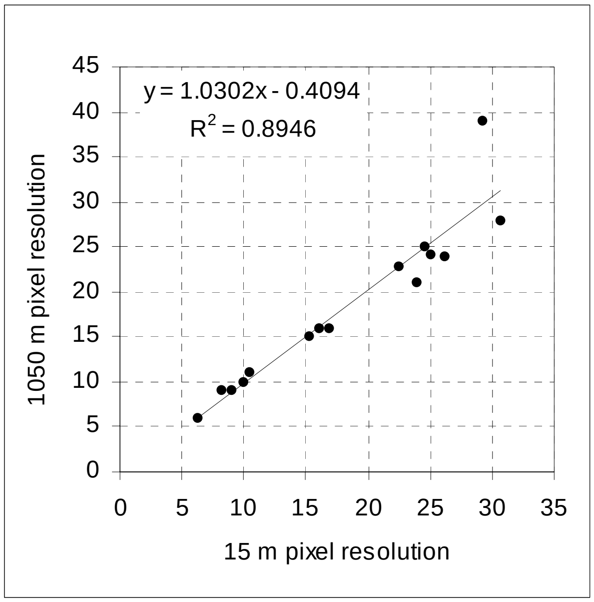

Fig. 2. Linear regression between mean slopes of watersheds obtained from the 15-m resolution map and the 1050-m resolution map.

Hill Reservoir Suitability Map

The map resulting from the multi-criteria analysis identified a total area suitable for hill reservoirs of about 1291 ha, representing 1% of the area under study (Fig. 3). Watershed area is the most restrictive criterion, covering 1482 ha, and the mean-slope is the least restrictive with 98,343 ha. This suitable slope extends over the whole study area excluding the plain bordering Oued Rmel River and the steep Zaghouan Mountain. The more than 96,000 ha difference between the watershed-area criterion and mean-slope criterion is expected. Indeed, the watershed area is represented by only one pixel located on the hydrographic network. However, the mean-slope is represented by several pixels covering the entire watershed.

Validation

The additional nine hill reservoirs identified in 2003 are used to check the reliability of the suitability map for hill reservoirs. Indeed, all these reservoirs match in the suitable class of this map (Fig. 3). These results indicate the consistency of the methodology for identifying potential sites for hill reservoirs using data derived from a DEM.

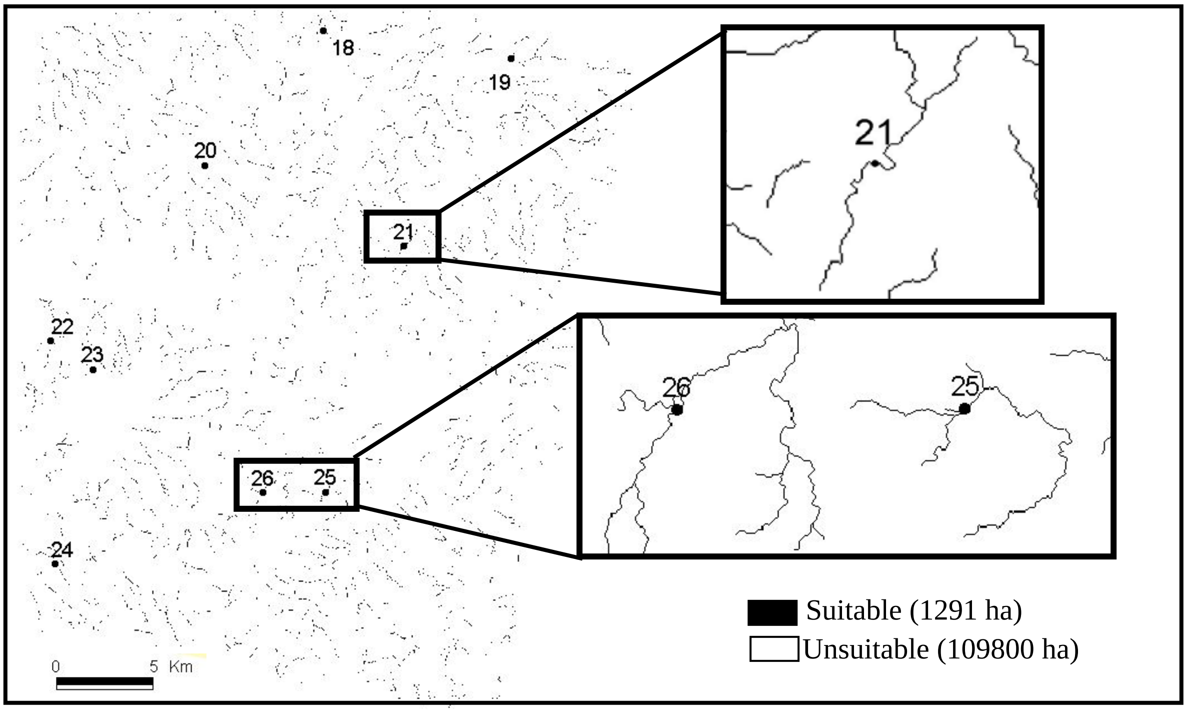

Fig. 3. Hill reservoir potential sites map of the study area.

Conclusions

In this work a single-objective multi-criteria analysis was carried out to identify potential sites for hill reservoir structures in a semi-arid area of Tunisia. Two criteria were selected; hill reservoir watershed area and watershed mean-slope. Their corresponding maps are derived from a DEM. An ASTER DEM was used for this study, however, other kind of DEMs such as SRTM or GTOPO30 (Verdin et al., 1996) are likewise useful. These DEMs are almost free, offering the possibility to extend this methodology to other areas with almost no charge.

The methodology developed follows a bottom-to-top approach in a way that it starts with characterizing watershed areas and mean-slopes of existing hill reservoirs and based on this characterization extrapolates the data to a larger area. Assigning to each hill reservoir a representative pixel and assuming an unique watershed size and form have been essential for obtaining a potential map for hill reservoirs.

The methodology stresses the way hill reservoir watershed area and watershed mean-slope maps are derived from a DEM and how they are combined in a single-objective multi-criteria analysis. However, to identify the final potential sites for hill reservoirs other criteria expressing the water quality and its possible use have to be incorporated in the process, such as geology and land cover of the watershed, accessibility to the hill reservoir and socioeconomic aspects.

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