Assessment of Supplemental Irrigation and Water Harvesting Potential

Methodologies and Case Studies from Tunisia

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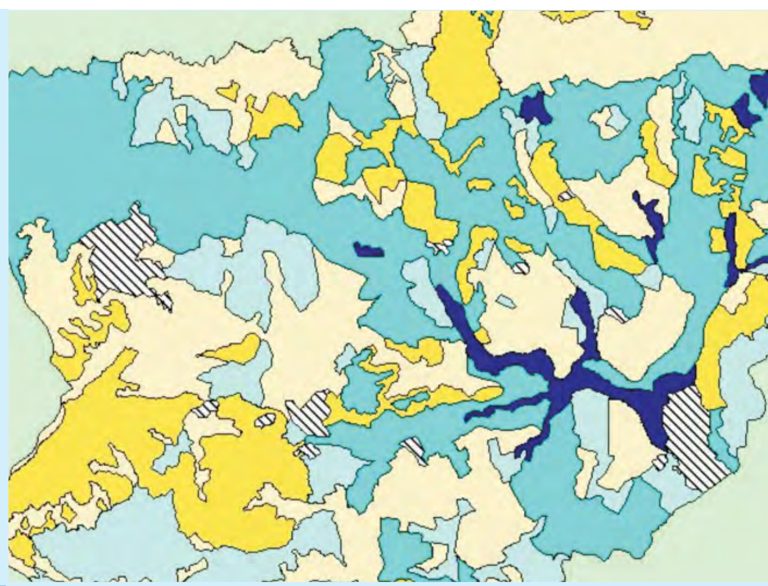

COMPREHENSIVE Assessment Of water management in agriculture

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International Center for Agricultural Research in the Dry Areas

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CONTENTS

ABSTRACT

An innovative, low-cost methodology was developed to assess the potential of sites in Tunisia for supplemental irrigation and water harvesting. The methodology, which uses commonly available technologies and information such as remote sensing and a Digital Elevation Model (DEM), was developed and tested using newly constructed hill reservoirs (used to capture surface runoff) and traditional water harvesting systems.

Supplemental irrigation potenatial was studied in a pilot area, Oued R'mel in north-eastern Tunisia, Starting with currently operational hill-reservoirs, Aster images and DEM files were used to map sites suitable for intercepting water along short-lived watercourses. Indices to describe land suitability for irrigation were derived by combining qualitative soil information with DEM data. The outscaling operation from pilot site to the entire country was carried out through several steps, taking into consideration changes in suitability attributes related to changes in rainfall. The end product was an overlay of areas suitable for constructing hill-reservoirs on a map of soils receptive to irrigation, on a scale of 1/500000.

Traditional water harvesting systems were studied at a pilot watershed, Oum Zessar, in the hilly arid (rainfall < 250 mm) area of southern Tunisia. The study focused on techniques used on steep slopes (*Jessour*) and piedmonts (*Tabia*). Slope and size of the watershed (separately) were the main criteria for defining land as suitable for *Jessour* and *Tabia*. Through iterative operations, we found optimums for pixels aggregation to set suitability conditions. The analysis also included geo-referenced data on local population in order to identify socioeconomic factors that could determine success. The most important factor was direct involvement of local farmers in water harvesting and use.

Key words: digital elevation model, satellite images, spatial representation, land suitability, hill reservoirs.

PART I. SUPPLEMENTAL IRRIGATION POTENTIAL

1 INTRODUCTION

Rainfall variability is the most important factor limiting agricultural production in North Africa. Precipitation occurs sporadically, with large annual and seasonal variations. The recurring deficiency of soil moisture is reflected in highly variable crop yields. For example, cereal production typically varies by a factor of four from one year to another, depending on the amount and timing of rainfall. Despite the low yields, rainfed agriculture is vital to national economies, plays a key role in maintaining social stability, and accounts for a large share of employment.

Many water conservation strategies have been developed in North Africa. Most methods have focused on improving the performance of irrigation systems; some on adapting crop management systems to reduce the need for irrigation water (particularly during summer). In some cases, farmers have been encouraged to stop growing crops that do not have a comparative economic advantage. For instance, sugar beet and cotton are no longer produced in Tunisia.

Yield-enhancing technologies have been adopted at different scales. These technologies range from modern irrigation techniques to high-yielding cultivars grown with high levels of inputs such as nutrients and pesticides. Total agricultural production has risen significantly, but North Africa still suffers from a large gap between food needs and production. In the 1990s agricultural growth rates were zero – and even negative in some countries – because of water shortages and severe droughts.

Innovative techniques that ensure the best use of natural precipitation need to be developed. Traditional options based on full irrigation with intensive cropping systems are probably not the best choice anymore, because of chronic water shortages.

Many research studies show that in environments characterized by alternating wet and dry seasons, adding small amounts of water during the growing season can increase water productivity many-fold. This potential of supplemental irrigation must be explored to make better use of the limited resources available.

This report describes a methodology to identify potential areas for developing supplemental irrigation systems. Development of the methodology built on past experience with building small reservoirs to collect water. Existing structures were used as a starting point to map potential sites for harnessing runoff water, following a 'bottom-up' approach. As for soils, a capability index for irrigation was calculated for each soil unit reported in the descriptive soil map of Tunisia. Regional suitability for supplemental irrigation was obtained by overlaying the two maps.

2 CHARACTERISTICS OF THE PILOT AREA

2.1 Available water resources

Water resources in Tunisia are characterized by large variability in both time and space. In terms of spatial variability, mean annual precipitation ranges from 1500 mm on the peaks of the Kroumirie mountains in the north-western corner of Tunisia to less than 100 mm in the south. Out of a total land area of 155000 km^2, non-arid area is estimated at 37,000 km^2 (24%), arid area 55,000 km^2 (35%) and desert 63,000 km^2 (41%). Variability in time is very high both within and between years. Mean total precipitation is 36 km^3 of which only 3 km^3 could be potentially collected as runoff water in large dams. Renewable groundwater resources are estimated at 1.8 km^3.

In Tunisia, as in other Maghreb countries, rainfall is almost the only source of fresh water. Table 1 shows the water resources available in Algeria, Morocco, and Tunisia.

Seasonality of precipitation also depends on the relief and on proximity to the Mediterranean Sea.

Table 1. Water resources in North African countries (source: Aquastat-FAO, 2008)

	Precipitation	Renewable water resources	
	(km³/yr)	(km³/yr)	(m³/inhab/yr)
Algeria	211.4	14.3	435
Morocco	154.6	29.0	918
Tunisia	33.8	4.5	455

In contrast to some Mediterranean locations, summer rains are important in many arid parts of Tunisia. They occur at high elevation, above 1000 m, and may amount to 20% of the total. In the lowlands close to the coast, rainfall maximums occur during autumn. Moving towards the high plateaus located inland, rainfall maximums shift significantly towards spring. Storms of 30 mm/day also are more frequent in inland areas, highlighting the fact that areas with similar annual (total) rainfall might still require different water management practices. Fig. 1 summarizes the extent of rainfall variability in Tunis.

2.2 Production systems

Tunisia is largely arid, as a result of low average rainfall. Production systems could be classified under three categories: Forests and Highland mixed, Rainfed and Irrigated mixed, and Oases and Dryland Pastoral systems. The cultivated area is partitioned almost equally between cereals (34%), olive plantations (33%) and other Mediterranean crops and fallow (33%). The ratio of potentially irrigable land to arable land is as low as 9%, reflecting the scarcity of water in the country. Most agricultural systems are rainfed, with cereals and olive trees as dominant activities. Livestock production is also very important in all regions; 70% of farmers keep livestock.

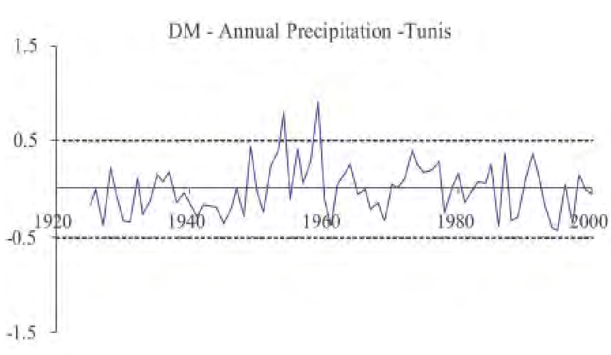


Figure 1. Deviation from mean (DM = P/Pm – 1) of annual precipitation, typical of semi-arid Mediterranean environments (Tunis station, 1925-2000)

Although water is crucial to all agricultural systems, vulnerability to drought varies significantly across the different agro-ecological zones. The impact of water deficit on agricultural production ranges from a simple yield reduction to a total failure of the production system.

Bioclimates within rainfed agriculture

Rainfed production systems include three types. Conditions within each of these bioclimates, and practices used to supplement rainfall deficiency, are summarized below.

***Subhumid, annual rainfall above 550 mm*.** Here, rainfall is sufficient for most winter crops; runoff usually occurs on saturated lands. Collection of surplus water in reservoirs and ponds is possible. However, low soil fertility and the practice of grazing on sloping lands could be a serious constraint to the development of irrigation. Hill-reservoirs were installed first in the sub-humid regions, before being extended to semi-arid environments.

Higher semi-arid, annual rainfall 400-550 mm. Some annual crops (e.g. cereals) and Mediterranean tree species are grown extensively. They can ensure sustainable production on deep soils.

Sloping areas, however, have shallow soils and need specific management in order to retain runoff water. While terraces and embankments are common, the construction of hill-reservoirs has been also successful in these areas. Supplemental irrigation ensures more dependable yields. Moderate salinity in irrigation water with a total dissolved solute content (TDS) up to 2.5 g/l is not considered to be detrimental to the winter production of many crops like olive trees, wheat, barley, forage grasses etc. However, adoption of irrigation generally depends on the availability of skilled labor, production inputs and access to nearby markets.

Semi-arid, annual rainfall 250-400 mm.
Various water harvesting and supplemental irrigation practices are used. Special micro-catchment techniques, locally called *meskat*, are extensively used (300,000 ha) in the coastal undulating area where mean annual rainfall is around 300 mm. In the central plains, the most common method for rainwater harvesting is to build structures within *wadis* to divert and spread the flow of water.

The relative importance of major agricultural sectors in countries comparable to Tunisia in North Africa is summarized in Table 2.

2.3 Feasibility of supplemental irrigation

Along with the development of irrigation projects, many studies on crop water requirements have been carried out in Tunisia from the 1930s onwards. Volumes of information are available on water consumptive use of many crops and tree species. This knowledge is particularly important in the domain of using saline water for irrigation, due to the low quality of the water available in the country. A review of relevant research on trees is presented by Ben Mechlia and Masmoudi (2003).

Research has shown the quantitative relationships between production and water supply. Thus the work on olives carried out in Tunisia sought to evaluate the potential of using different irrigation amounts to complement rainfall. Results showed that olive production was almost unchanged when water supply increased from 300 to 650 mm/year in addition to the 450 mm of rainfall. The use of saline water (4.7 dS/m) in this experiment led to similar conclusions.

For leaching, precipitation of about 500 mm helped to remove salts from the 0-125 cm soil profile, whereas amounts higher than 600 mm were needed for the leaching processes to reach the 125-200 cm stratum. These results suggest that adding water with total dissolved solids of about 3 g/l to olives grown on small parcels can improve productivity without being detrimental to the environment, provided the rainfall regime and soil structure allow for natural leaching of salts without contamination of aquifers.

In the central zone of the country (Ksar Ghriss), with an annual rainfall of 200 mm, irrigation amounts ranging from 450 to 950 mm/year produced the same yield on young olive trees. Furrow irrigation gave satisfactory results in terms of productivity and salinity control. Adoption of drip systems to deliver 400 mm/year resulted in a small yield increase (15%), although two surface applications were provided: one at the start of the irrigation season for good moisture setting under the drippers and the second at the end to leach the salts (Bouaziz 1983).

Table 2. Cultivated and irrigable areas for North African countries (source Aquastat-FAO 2008)

	Permanent crops (‘000 ha)	Arable land (‘000 ha)	Irrigation potential (‘000 ha)
Algeria	670	7545	510
Morocco	892	8484	1664
Tunisia	2140	2790	560

Under normal conditions, irrigation is applied for the purpose of optimizing crop production. For maximum yield one may avoid water stress by supplying all the water needed by crops. In water-scarce regions, water stress may not be avoided by maintaining a uniformly high moisture level in the soil, since an irrigation schedule that always maintains a fully charged root zone does not provide adequate opportunity for taking advantage of rainfall and/or stored soil water.

Should full irrigation be used to produce maximum yield on a small portion of the total area, or is it preferable to accept lower yields but over larger areas? This has been an important issue in developing supplemental irrigation programs. Another major issue evolved from the need to improve water productivity under conditions of erratic rainfall. There is a consensus that under water scarcity, irrigation should be discontinued in growth stages where yields are least susceptible to water stress, supporting the concept of Supplement-Deficit irrigation. Crops should be deliberately allowed to sustain some degree of water deficit and yield reduction in order to save water.

A range of options is available for supplemental irrigation. The technique could be applied in large-scale irrigation perimeters based on large dams and conveying systems or in small-scale irrigation from shallow wells or small reservoirs where runoff water is collected.

2.4 Development of supplemental irrigation

When applied in winter, irrigation has the potential to reduce spatial and temporal yield variability and improve productivity of crops that are normally grown under rainfed conditions.

The impact of supplemental irrigation on yield could be estimated using a simple model:

$$Y = A\,(Q – Q_0) \quad \text{........................(1)}$$

where Y is yield (t/ha), A represents the water marginal productivity of the crop, which varies from 0.004 to 0.020 t/mm in wheat. Q is the total water used (mm), Q_0 is the minimum amount of water (mm) required to produce vegetative growth (about 150 mm in the Tunis region).

Table 3 shows improvements in wheat yields as a result of supplemental irrigation over four years of cultivation in the region of Tunis.

In winter, deficit irrigation could be practiced successfully, i.e. water will not be added to fully complement rainfall. Only small amounts are applied at specific growing stages when irrigation can have maximum impact. Under such circumstances, scheduling is the key factor. Table 4 shows how sophisticated scheduling can improve the level of irrigation adequacy without proportionately reducing wheat yield.

A schedule that will guarantee optimal income is the essence of restricted supplemental irrigation. Optimum is reached when the marginal revenue from the yield, calculated from the crop production function, equals the unit price of water. One limitation to applying this strategy relates to the uncertainty involved in using long-term production functions and weather data. Actually, it is often difficult to predict water-crop yield relations, particularly for winter crops.

In conclusion, supplemental irrigation has emerged during the last few decades as an appropriate technology that has the potential to improve wheat productivity and at the same time to reduce spatial and temporal production variability. It has been adopted in different parts of the Tunis region, and even institutionalized as a major strategy to respond to growing water scarcity and at the same time to increase crop productivity in traditionally rainfed areas. However, due to the limited available water resources, development of this technique should target the most profitable areas where the allocation of irrigation water could be optimized.

Another major outcome of the water resources development programs that could be directly related to supplemental irrigation, is the construction of new hydraulic structures to collect water in semi-arid areas. Hundreds of small reservoirs

Table 3. Wheat yield under supplemental irrigation (SI) with Medjerdah waters. Tunis, mean of 4 years (Ben Mechlia 2003)

	Irrigation (mm)	Effective rain (mm)	Yield (t/ha)
Rainfed	0	387	3.3
SI (planting)	70	387	3.6
SI (planting and anthesis)	140	387	4.8

Table 4. Irrigation, yield, and water use efficiency under different scheduling strategies in wheat (Ben Mechlia 2003)

	Rainfed	Full SI	SI, best scheduling	SI, poor scheduling
I (mm)	0	195	115	140
P+I (mm)	270	465	385	410
Yield (t/ha)	0.02	5.8	4.4	0.7
IWUE (kg/m^3)	-	2.9	3.8	0.5
TWUE (kg/m^3)	0.07	1.25	1.15	0.18

I = irrigation, P = precipitation, IWUE = Irrigation water use efficiency, TWUE = Total water use efficiency, SI = supplemental irrigation

or *Lacs collinaires* as they are called locally, are operational in the northern part of the country, precisely the areas with high potential for supplemental irrigation.

2.5 The use of small reservoirs

Hill reservoirs or *Lacs collinaires* have been recently developed with the objective of collecting surface runoff from the catchment and storing it in small surface reservoirs in order to give farmers in remote areas access to water (Fig. 2).

With watersheds of a few hundred hectares, the excess rainwater not allocated during the rainy season is diverted to storage in ponds and apportioned for irrigation. Their average capacity varies typically between 10,000 and 200,000 m^3 and the runoff area from 40 to700 ha.

In addition to their role in protecting the infrastructure from flash floods and sediment deposits, *lacs collinaires* are used as storage facilities. The water collected is mostly used for agriculture; almost never for drinking, since potable water networks cover most rural areas. Abstractions for watering livestock are negligible in terms of quantity, but important for livestock and natural pasture management.

Unlike large reservoirs, hill lakes are not permanent sources of water and their management is very site-specific. The state of the reservoir at the end of winter, i.e. in March, is of particular interest if late spring or summer irrigation is planned for vegetable crops.

Irrigation planning is mostly done through a participatory approach. The capacity of the reservoir to supply the required water is evaluated by the different users; farmers ensure themselves of all needed water and decide on the area that should be irrigated. Supplemental irrigation during winter does not involve strict commitments among farmers although large water amounts are involved. A survey conducted during a wet year showed that total water used was, on average, equivalent to 80% of reservoir capacity.

Figure 2. Hill reservoirs are constructed mainly in semi-arid regions with annual precipitation above 250 mm

2.6 Oued R'mel pilot site

The study area (Fig. 3) corresponds to an ASTER scene which falls mainly in Zaghouan, Nabeul and Ben Arous districts. This area, 1113 km2, is located in northeastern Tunisia. The climate is semi-arid. Zaghouan, the main city in the study area, has a mean annual temperature of 18ºC and a mean annual precipitation of 449 mm.

The altitude varies from 1293 m above sea level (a.s.l.) in Djebel Zaghouan to about 50 m a.s.l. close to Oued R'mel dam. With about 570 km^2 area, the Oued R'mel catchment is characterized by various soil types, land forms and land cover. The dam was built to supply water to the Bouficha irrigation district designed for production systems based on supplemental irrigation. In addition, more than 25 hill-reservoirs have been constructed in this area on small sub-watersheds and the area under supplemental irrigation is expanding.

3 LAND SUITABILITY FOR SUPPLEMENTAL IRRIGATION

Suitability of lands for agriculture is related to their potential for making water and nutrients available to plants. Water availability is de-

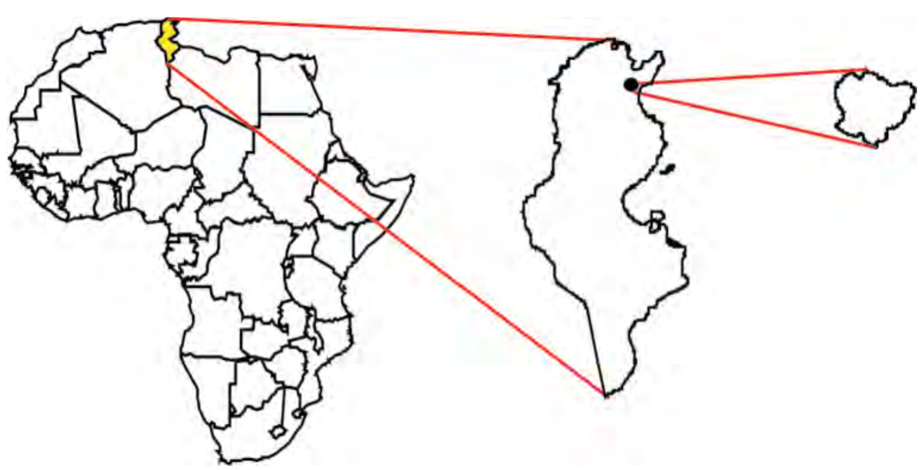


Figure 3. Pilot area of Oued R›mel used for developing the methodology for determining soil suitability for supplemental irrigation in Tunisia

termined by climate and the morphological, physical and chemical properties of the soils. To identify lands suitable for supplemental irrigation, precise quantitative soil surveys and several costly and time consuming field measurements are needed, unless an appropriate methodology using commonly available information and new technologies such as remote sensing is developed.

Information on soils in North Africa usually follows the French procedure on soils reporting and mapping. For Tunisia, the country soil map is produced according to the classification system of Aubert (1965).

3.1 Soils of the pilot site

Available studies and maps on soils of Tunisia provide mostly qualitative information rather than systematic, quantitative data on physical and chemical characteristics. Within the study area, three soil classes grouping ten soil units are found (Fig. 4).

The major soils of the pilot area (83%) are of the Calci-magnesic type. They are found in the mountainous and undulating areas surrounding the plain of Oued R'mel valley. Alluvial soils (16%) are typical of the flat and rolling areas along the valley. Red Mediterranean soils are constrained in the massif of Zaghouan. On the map, soil units are given at group or sub-group level according to the French system and they correspond to pure soil types or associations between various soil types.

According to Aubert (1965), Calci-magnesic soils are characterized by high amounts and marked influence of calcium carbonate or calcium carbonate and magnesium or calcium sulfate within the soil profile. Two major sub-classes are

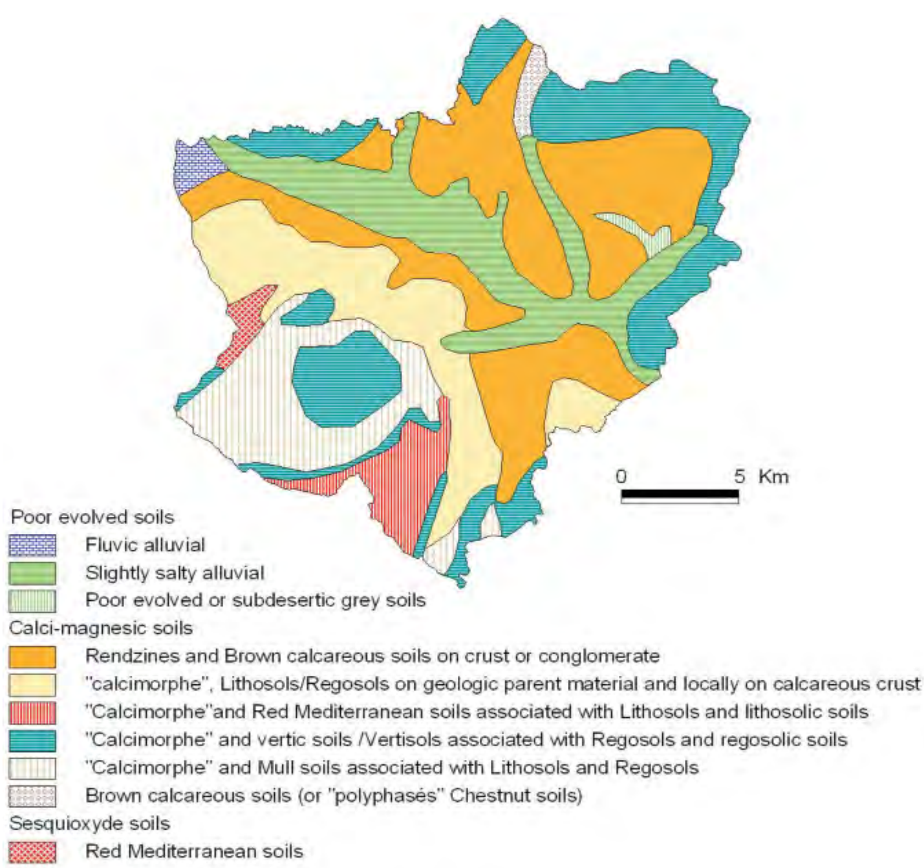


Figure 4. Soil map of Oued R'mel catchment, according to the French classification (Aubert 1965)

considered: soils developed on calcareous material called Rendziniforme, and those developed on gypsum material. Within the study area, only Rendziniformes are found. Among these, three soil types can be considered:

- Rendzine soils which are characterized by an AC profile type and by loamy or silty clay texture classes. Their geographic position in high relief makes them appropriate for forests.
- Brown calcareous soils, characterized by an A(B)C profile type, are deeper and less erodable than the Rendzines. At high altitude (400-600 m), they are suitable for reforestation and range respectively, in changing and regular relief. In piedmonts with regular slopes, brown calcareous soils are suitable for agriculture, especially for growing cereals, fodder and tree crops.
- The third type corresponds to 'calcimorphe' soils developed on calcareous accumulation. Characterized by shallower depth and loamy to fine texture classes, they are considered to be suitable for cereals and tree crops such as olives and vines.

Alluvial soils have an AC profile type; the A horizon is thick and poor in organic matter content. They are deep (more than 100 cm), and have variable soil texture. Although suitable for agriculture, they can present some limitations related to drainage and/or salinization.

Red Mediterranean soils, located in Zaghouan Mountain, are basically formed on gray or dolomite calcareous material. They are eventually covered by natural forests formed mainly by *Pinus halepensis.*

Our task was to produce a suitability map with straightforward indications of suitability for irrigation. Although the available information on soil, based on the French classification, is useful for agronomists and soil specialists acquainted with sophisticated technical terms, it does not provide an easy evaluation of the land potential for developing irrigation. Other classification systems based on quantitative soil properties are more appropriate for assessing suitability for irrigation. Translating descriptive information about soils to clear-cut quantitative data will enable the use of standardized land evaluation methods for assessing suitability.

3.2 Methods of land evaluation

USDA Land Capability Classification

The USDA-LCC considers eleven criteria including depth, texture, permeability, slope, erosion, flooding salinity and toxicity hazards. In this method, a total of eight classes with increasing limitation severity are recognized. Classes I to III are considered suitable for regular cultivation, Class IV for limited cultivation, and the remaining classes are dedicated to other uses. Actually, there are no specific needs for irrigated agriculture, but irrigation is considered only for soils with high production potential in order to compensate for the additional costs of equipment, labor and water (Minagri 2004).

Storie Index Rating (SIR)

The SIR was developed by Storie in the 1930s on the basis of productivity data from a number of major soils in California. It is based on soil characteristics that are believed to govern the "land's potential utilization and productivity capability". Four soil factors A, B, C, and X are rated from 1 to 100 points. The scores are then used to compute an SIR that ranges from 1 to 100. The characteristics of the soil profile (designated as factor A) are essentially features of the subsurface layer. Young alluvial soils deep and readily pervious to roots and water are rated 100; a soil with developed clay pan would rate between 40 and 80. The texture of the surface soils (factor B) is rated high when it is medium (loamy); the extremes in texture such as sands and clays are rated lower. Factor C refers to the slope. Factor X rates factors that are not included in the previous ones, i.e. conditions that are considered important to crop productivity, such as drainage and alkali and salt content. Subfactors under X are rated independently from

1 to 100 (Storie 1976). In spite of its inherent weaknesses, its simplicity made SIR one of the rating systems most accepted by investors in California.

Capability for irrigation (Ci)

A derived method with seven criteria was introduced by Sys et al. (1991) to assess suitability for irrigation. It is applicable to land units with homogeneous soil morphology, physical and chemical properties. It considers seven criteria: soil texture, slope, soil drainage properties, electrical conductivity of soil solution, soil depth, calcium carbonate and gypsum contents. Rating tables are provided to allocate (by interpolation) a score of 0 to 100 for each criterion (A to G). Table 5 shows a summary of tables used by Sys et al. (1991).

Capability for irrigation (Ci) is the product of the scores obtained for each criterion, A to G (eq. 2).

$$Ci = A \cdot \frac{B}{100} \cdot \frac{C}{100} \cdot \frac{D}{100} \cdot \frac{E}{100} \cdot \frac{F}{100} \cdot \frac{G}{100} \qquad \ldots\ldots\ldots\ldots\ldots(2)$$

Suitability for surface irrigation is then given by Table 6 where five classes are recognized according to the capability rating.

Mapping land suitability for irrigation using field surveys, the IAO approach

The method of Sys et al. (1991) is valid only at the site level, because quantitative measurements need to be obtained. When large areas are considered, many sites should be surveyed in order to account for any variability in soil properties.

The IAO (Istituto Agronomico per l'Oltremare) approach (Ongaro 1998) considers the landscape as a collection of land systems. Each land system has homogeneous geological features and is composed of one or more facets. Facets are assumed to have small variability in terms of geomorphology, physical and chemical properties. They are delimited using aerial photographs and satellite images as well as 1:50000 topographic maps. If the facet area is smaller than the minimum mapping unit, geomorphologically and geographically, contiguous facets are combined to obtain a facet which inherits the properties of the most representative one.

Physical and chemical properties of a given facet are determined from field measurements in one

Table 5. Criteria and indications for rating used in the Sys et al. (1991) method

Texture	Slope (%)	Drainage	ECe (dS/m) Clay types*	ECe (dS/m) Others	Depth (cm)	$CaCO_3$ (%)	$CaSO_4$ (%)
Clay Loam	0-1	Well drained	<4	<4	> 100	<0.3	<0.3
Silty Clay Loam	1-3	Moderately drained	4-8	4-8	80-100	0.3-10	0.3-10
Silty Clay	3-5	Imperfectly drained	8-16	8-16	50-80	10-25	10-25
Clay	5-8	Poorly drained	16-30	16-30	20-50	25-50	25-50
Silt Loam	8-16	Very poorly drained	>30	>30	< 20	>50	>50
Silt	16-30	Unspecified					
Sandy Clay	>30						
Loam							
Sandy Clay Loam							
Sandy Loam							
Loamy Sand							
Sand							

	Rating
green	100
blue	80-100
light blue	60-80
yellow	<60

* Clay, Sandy clay and Silty clay soils

Table 6. Correspondence between Ci rating and suitability for surface irrigation

Ci rating	Suitability for SI	Symbol
>80	Highly suitable	S1
60-80	Moderately suitable	S2
45-60	Marginally suitable	S3
30-45	Currently unsuitable	N1
<30	Permanently unsuitable	N2

or more sampling sites. Information about the relative areas of the facet and/or the quality of the fieldwork is used in the process of generalization from sites to facet and from facets to land system.

The IAO methodology was applied recently to Oued R'mel catchment (IAO 2004). The fieldwork covered 95 sites distributed within the pilot area. Soil profiles were described and soil samples analyzed. Capability rating (Ci) was determined for each site. The process of generalization, described earlier, was used to produce a suitability map for surface irrigation (Fig. 5).

The approach we are proposing is an alternative to the IAO method. Instead of time and resource consuming surveys, it uses existing soil information and a Digital Elevation Model (DEM) to map land suitability for surface irrigation. Parameters as required by the Sys et al. formula are derived quantitatively from the qualitative information found locally.

Deriving suitability for irrigation (Ci) from soil maps and DEM

Existing information covers soil profile types, parent materials, presence or absence of crusting or encrusting material, dominance of eroded soils (Lithosols or Regosols) and association between deep and shallow soils. The task is to transform this descriptive information into quantifiable soil properties. Interpretive methodology is used to derive soil depth, soil texture class, drainage properties, calcium carbonate, sulfate and salinity status. Slope gradient (%) is derived from the DEM.

Results presented in Fig. 6 show that alluvial soils which follow Oued R'mel major bed are the most favorable for surface irrigation, followed by soils localized in undulating and rolling areas which correspond to calci-magnesic soils. Red Mediterranean soils located in the massif of Zaghouan are classified as unsuitable for surface irrigation not because of their calci-magnesic nature, but because of high slopes, since they are located in the surrounding mountains.

4 SUITABILITY FOR HILL RESERVOIRS

The technical feasibility of supplemental irrigation depends on the availability of adequate water, both from rain and from irrigation. Its success depends on the availability of appropriate infrastructure for implementing irrigation programs within areas of productive lands.

Rainfall amount, watershed area, land use and mean slope determine the runoff water which can be stored in a hill-reservoir. However, sizing and siting of the reservoir depend on technical, socioeconomic and environmental factors. While determining the potential for runoff water collection in hill-reservoirs in this study, only physical factors were taken into account.

We describe a new methodology to map areas suitable for hill-reservoirs. Starting from a situation where these structures have been successfully implemented in the pilot area, our objective was to identify the physical criteria for their success. The proposed methodology involves four steps: i) identifying existing hill-reservoirs from satellite images and determining their watershed areas from DEMs, ii) determining the size and slope of identified watersheds, iii) deriving potential sites for hill-reservoir construction in the pilot area, and iv) validation of the methodology.

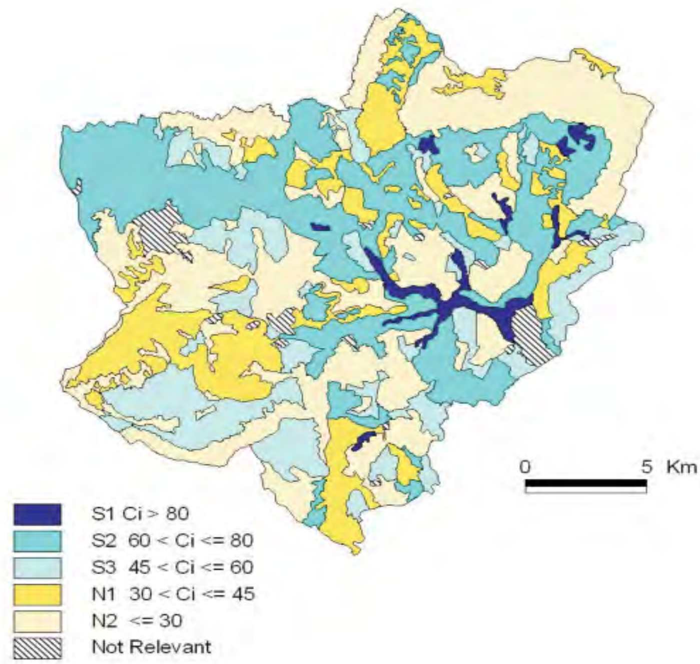


Figure 5. Capability rating (Ci) for surface irrigation in Oued R'mel catchment, using IAO methodology

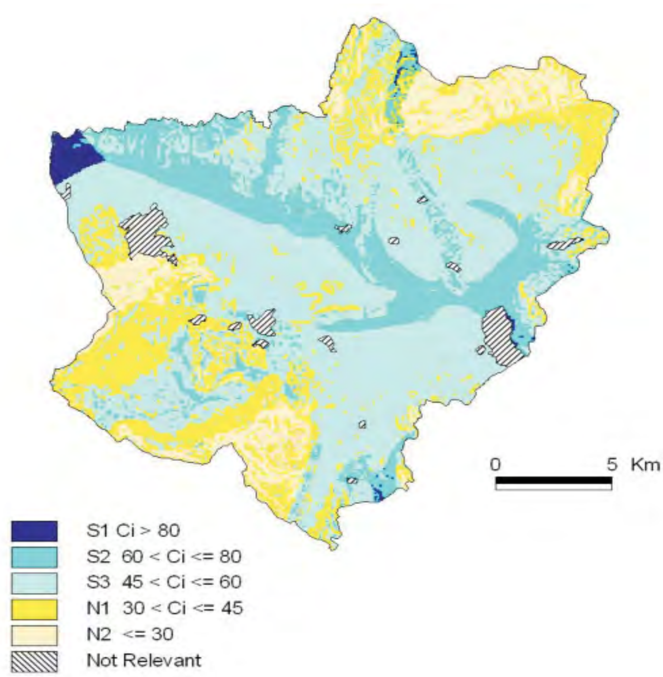


Figure 6. Map of Oued R'mel catchment showing land suitability rating for surface irrigation as derived from the soil map of Tunisia and DEM

4.1 Identification of existing hill reservoirs from satellite images

The ASTER image of 2001 was displayed in the false color composition RGB 321 bands (NIR, Red, Green). This composition shows water bodies in black color that could be identified visually in the image.

For better reliability, an automatic method was chosen instead of visual identification. After geometric correction, a decision tree class identifier technique was used to localize water surfaces (Chuvieco 2002). The criteria adopted for red and near infrared were Digital Number (DN) <21 and DN <28 respectively. These threshold values allow separation of water bodies from all other land covers except mountain shadows. Separation of water bodies from mountain shadows was obtained by a threshold value of DN >26 for the green band. Persistent small groups of pixels were eliminated by a sieve operation.

The procedure resulted in the identification of hill-reservoirs, visually checked on the image for water surfaces and dikes. Overlay of the identified reservoirs on the hydrographic network was also used for double checking.

Use of this method on the whole ASTER 2001 image allowed the identification of 17 hill-reservoirs at that date. The area of each water body was determined and a vector layer was generated. Figure 7 shows an overlay of the Aster image and point layer representative of the identified hill-reservoirs.

4.2 Determination of watershed area and slope of existing hill reservoirs

A suitable watershed area and mean watershed slope for implementing hill-reservoirs could be determined from the identified hill-reservoirs. DEMs were used to derive these values. The Shuttle Radar Topography Mission (SRTM) DEM with 92.5 m resolution, available for the entire country, and an Aster DEM of the pilot area, with 15 m resolution, were used.

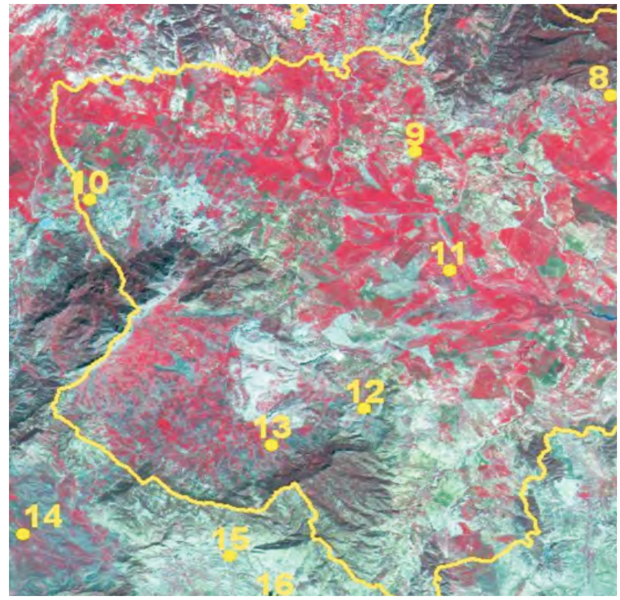


Figure 7. Distribution of reservoirs in year 2001 in the surveyed area

The SRTM DEM files covering the entire country were joined, then re-projected from geographic lat/long projection to Conic Lambertien projection. The resulting DEM with 92.5m x 92.5m spatial resolution was corrected by filling sinks and used to extract the area corresponding to the pilot site.

The ArcView Hydro tools extension (Schäuble 2003) was used to produce a flow accumulation grid. Each cell of the grid contains the value of the contributing area, i.e. the number of cells whose flow path passes through that point (Burrough and MacDonnell 2001).

In order to systematize the processing, each hill-reservoir was identified by a single pixel. The representative pixel was taken as the one with the highest value of flow accumulation lying in a one-pixel buffer zone outside the water surface to avoid low precision of the remotely sensed DEM related to water. For the Aster DEM a buffer of two pixels was used.

Representative pixels for the 17 identified reservoirs were selected, and the corresponding watershed boundary, area and average slope were determined by the hydro-watershed extension (Schäuble 1998). The areas and slopes obtained are reported in Table 7. The resulting range of the watershed areas of the identified hill-reservoirs seemed to be too wide (9 ha to 1406 ha). In fact, the reported watershed sizes of hill-reservoirs in the study area and in neighboring districts are 40-700 ha (Minagri 2004).

Cross validation was done with data reported by the Ministry of Agriculture and by the results obtained using the Aster DEM (15x15 m). The smallest watershed area (reservoir 7) was found to be 37 ha after appropriate correction using the Aster DEM. Reservoir 16 was ignored, because it is too large to be considered a hill-reservoir by local standards.

The average watershed and median areas were respectively 213 ha, and 176 ha. The mean slope of the identified watersheds was in the range 3-26% with a mean of 13.3% and a median of 12%. These values were used for extrapolation to the entire study area.

4.3 Deriving potential sites for hill reservoirs

Any systematic procedure for identifying suitable sites from satellite images should be based on grid algebra. The DEM and satellite images are geo-referenced grid files where a pixel represents an area related to the resolution of the grid file. In the 92.5-m resolution SRTM DEM file, a pixel represents an area of 0.855 ha.

Some assumptions were made in order to apply grid-based GIS and remote sensing tools to

Table 7. Hill-reservoir watershed characteristics (area, mean slope and Gravelius compactness index) as derived from 15-m Aster DEM and 92.5-m SRTM DEM

	15m ASTER DEM			92.5m SRTM DEM		
Reservoir identifier	Area (ha)	Slope (%)	Compactness Index	Area (ha)	Slope (%)	Compactness Index
1	635	25	1.40	645	19	1.22
2	132	25	1.58	176	16	1.29
3	58	17	1.47	9	7	1.23
4	217	15	1.27	221	12	1.15
5	487	16	1.42	377	12	1.25
6	312	17	1.56	317	12	1.32
7	37	26	1.68	56	17	1.52
8	144	29	1.75	140	23	1.59
9	139	8	1.36	129	5	1.15
10	197	10	1.61	224	12	1.75
11	56	9	1.26	54	6	1.18
12	317	26	1.24	318	20	1.07
13	215	31	1.36	200	26	1.20
14	108	6	1.37	169	3	1.48
15	197	24	1.59	205	18	1.32
(16)	(1413)	22	1.43	(1406)	16	1.18
17	151	10	1.30	175	6	1.14

identify suitable watersheds and sites. Typical size of watershed was taken as the size of a square shaped cell, which is an aggregation of cells having DEM resolution. The size of 168 ha, obtained by aggregation 14*14 (92.5 m resolution) pixels, was the nearest value to the median watershed area, and was therefore adopted as typical size. An aggregated cell was considered as suitable if its average slope lay in range of 3-26%. The overlay of suitable cells re-sampled at 92.5 m resolution and the contributing area map allowed selection of cells having contributing area within the range 40-645 ha. The resulting map represents potential sites for hill-reservoirs.

This procedure allowed us to localize suitable sites for hill-reservoirs in the pilot area. Overlay with hydrographic map and water bodies showed that 14 hill-reservoirs out of the 16 previously identified were on potential sites (Fig. 8).

4.4 Validation

The methodology was validated using a more recent ASTER image (2003) from which 10 additional hill-reservoirs were identified (Fig. 9). An overlay check showed that all of them are within the derived potential area (Fig. 10).

5 OUTSCALING

Water harvesting and supplemental irrigation are technologies with proven efficiency in dry areas, and can help improve agricultural productivity in West Asia and North Africa. We have presented a methodology to evaluate potential areas where these technologies could be successful. Building on the promising results obtained from the pilot sites, the possibilities of outscaling are being explored.

In this section we first present the basic data (DEM, rainfall and soil data) used in the development of the methodology, and then discuss issues of outscaling. The final result is obtained by combining satellite information with commonly available data. The derived country map shows capability for irrigation and potential sites suitable for constructing hill-reservoirs.

5.1 Digital Elevation Model

The DEM of Tunisia was developed from the SRTM DEM (NASA). Files covering the entire country were downloaded, converted to Arcview raster format; then joined and re-projected from geographic lat/long projection to Conic Lambertien projection. The resulting DEM with 92.5m x

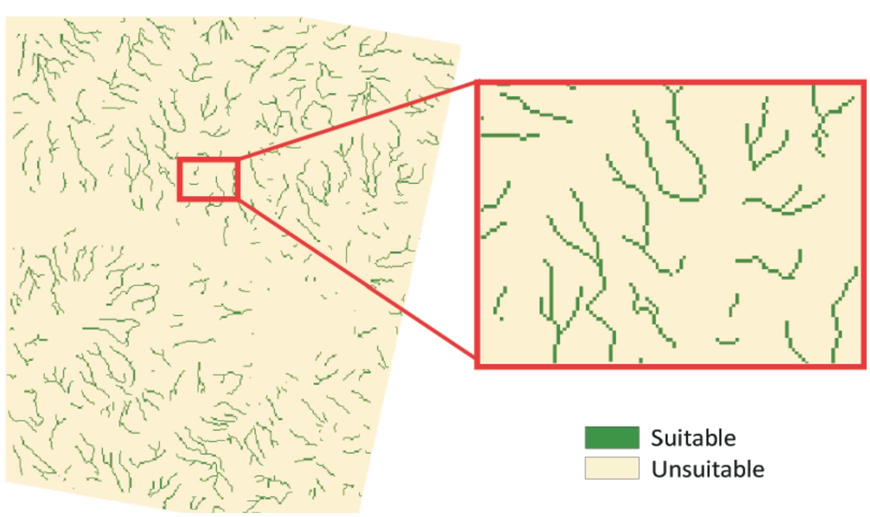


Figure 8. Potential hill-reservoir sites in the study area

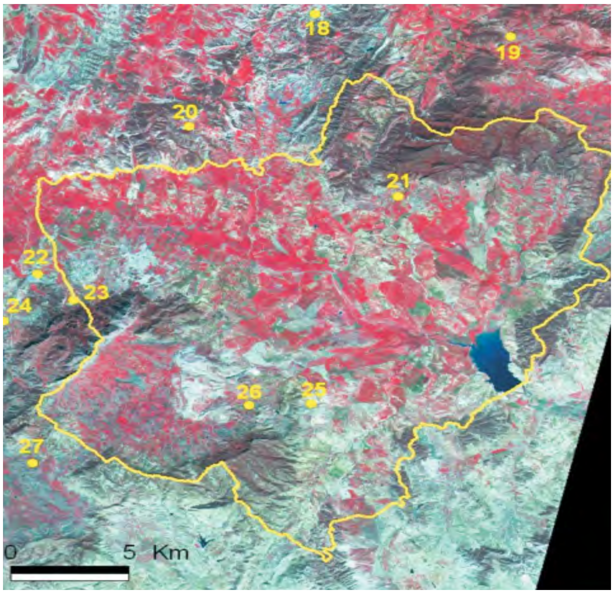


Figure 9. New hill-reservoirs (yellow points) identified from 2003 ASTER image shown on 2001 ASTER image background

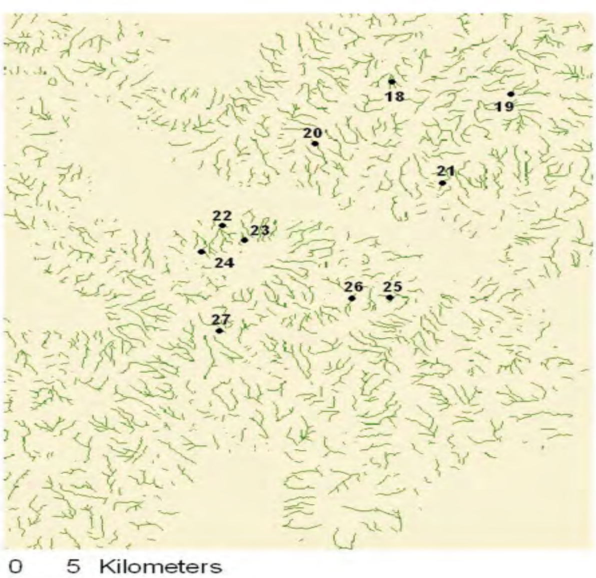


Figure 10. Validation of the methodology: 10 new hill-reservoirs not used for methodology development were found to be located at suitable sites

92.5m spatial resolution was corrected by filling sinks (Fig. 11). The DEM is essential for deriving slope and flow accumulation maps.

5.2 Rainfall

Monthly precipitation data from 40 precipitation stations (FAO climatic database Africa 2000) was used to derive the precipitation map (Fig. 12).

5.3 Soil map

The soil map of Tunisia, based on the classification system of Aubert (1965), is available at 1:500,000 scale. Soil units are given by class, sub-class, group and sub-group. A total of 61 units have been described for the country. The map was digitized and integrated in the Arcview GIS system. Fig. 13 shows the main soil classes as presented in the original map. For clarity, smaller units are not represented. Our work consisted of deriving quantitative data on soil characteristics from descriptive information. To this end, a matrix of 61 soil units by 15 soil factors was developed.

The following derived information was used as input data for the parametric method developed at the pilot site:

- soil texture
- slope gradient from DEM.
- drainage properties
- salinity-alkalinity status
- soil depth
- calcium carbonate status
- calcium sulfate status

5.4 Deriving suitability for supplemental irrigation

An area or location is suitable for supplemental irrigation when there is potential for adequate runoff and availability of receptive soils for irrigation. The occurrence of both conditions is examined by overlaying the previously produced maps for the pilot area (Fig. 14).

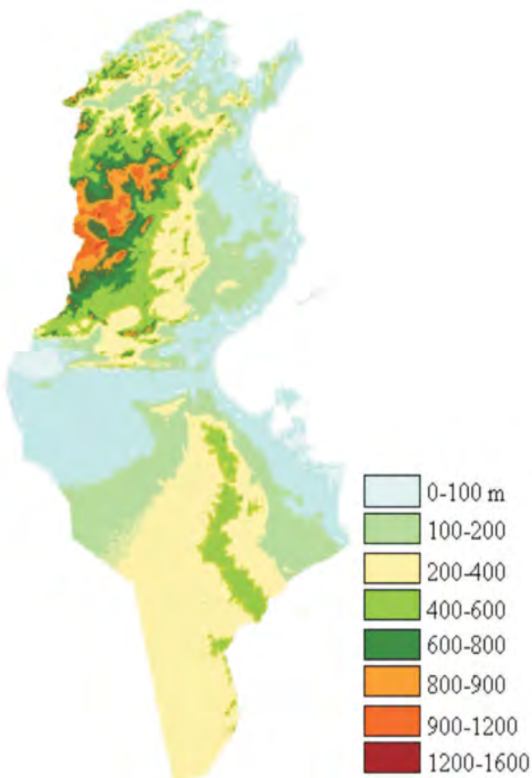


Figure 11. Digital Elevation Model of Tunisia

Figure 12. Precipitation map of Tunisia

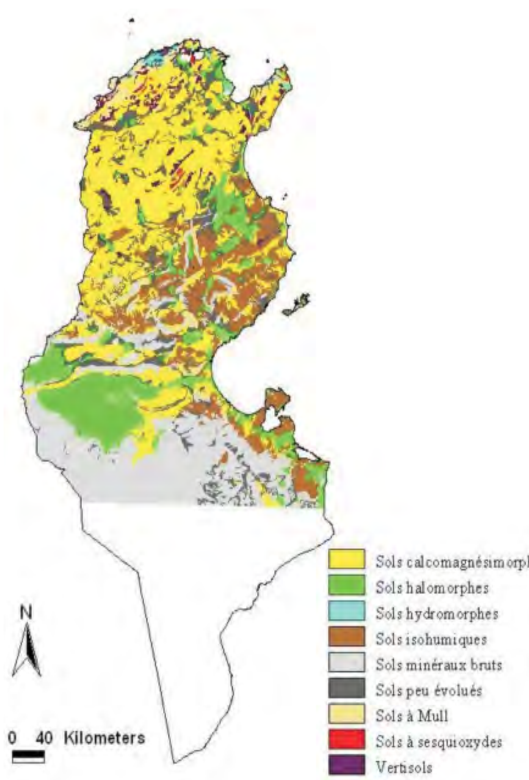


Figure 13. Soil map of Tunisia according to the French classification

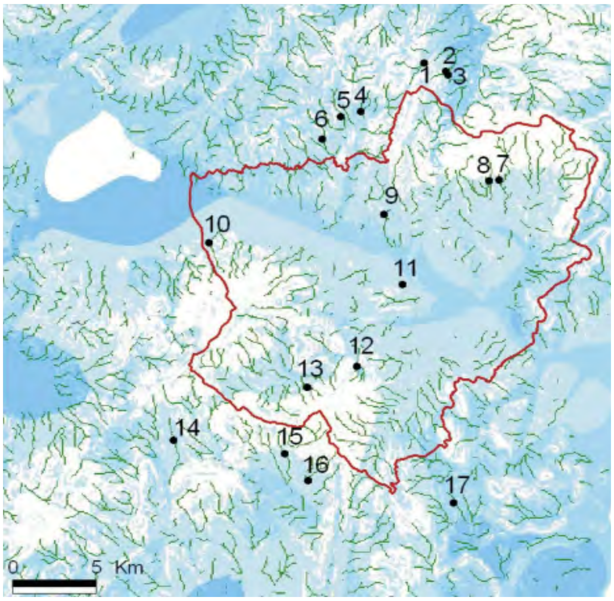


Figure 14. Suitability map of the pilot site showing: soils suitable for irrigation (colored background), potential sites for hill-reservoirs (green lines) and existing reservoirs (black dots)

5.5 Outscaling suitability for supplemental irrigation

The methodological development for hill-reservoirs was carried out in an area with average annual rainfall of 450 mm. Upscaling to the entire country needs appropriate corrections to account for variation in rainfall and water balance factors that may influence runoff regimes.

Suitable ranges of the contributing area need to be consistent with rainfall. To this end, the empirical formula of Tixeront (Cherif 1995), established for runoff estimation in Tunisia, was used to adjust for rainfall and evapotranspiration variation (eq. 3).

$$R = \frac{P^3}{3E^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where R is runoff (m), P is mean annual rainfall (m), E is mean annual evapotranspiration (m).

Mean annual rainfall and evapotranspiration maps were developed with 92.5 m resolution. Krigging was used to produce a rainfall map from point values (Fig. 12) while average values of evapotranspiration (E) were generalized for each governorate area. Equation (3) was then used to derive a runoff depth grid map for Tunisia.

The contributing area map for the entire country was also derived using the SRTM-DEM and combined with the runoff depth map to derive a map of runoff volume accumulation. Runoff volumes corresponding respectively to the smallest and biggest watersheds in the pilot area are taken as limits for suitability (13.1 to 208.1). A binary map of suitability according to this criterion was built and combined with a slope suitability map obtained by the 14*14 pixel aggregation-resampling procedure mentioned earlier.

Validation was performed using 665 hill-reservoirs surveyed by the Ministry of Agriculture and Water Resources in 2007. Overlay of the suitability map and the reservoir map shows a good correspondence between the actual location and the derived potential area (Fig. 15). Taking into consideration the different uncertainties involved

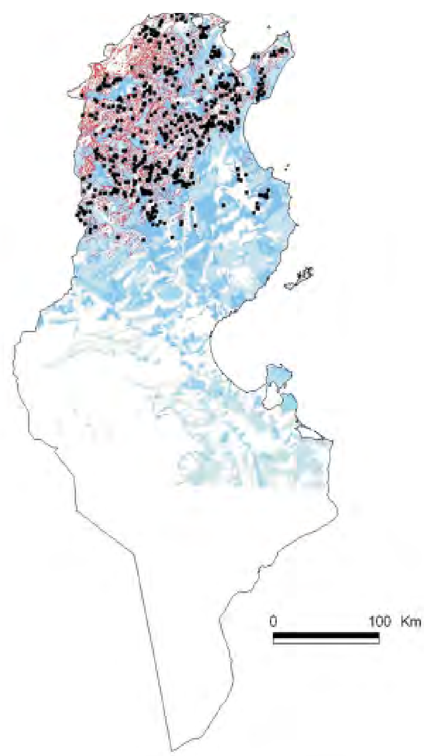


Figure 15. Map of Tunisia showing: areas suitable for surface irrigation (blue background), potential sites for hill-reservoirs (red background) and reservoirs actually implemented over the period 1967-2006 (black dots)

in applying this methodology, the percentage of operational hill reservoirs located exactly on the identified suitable sites was 11%. This perfect match increases to 42%, 67%, 77%, and 84% when we use a buffer zone of respectively 1, 2, 3 and 4 pixels of 92.5m.

6 CONCLUSIONS: SUPPLEMENTAL IRRIGATION POTENTIAL

In view of the huge impact of irrigation on agriculture, North African countries have based development plans on the construction of large dams. Population growth and the rapid development of many water consuming sectors have increased competition for water resources. To improve agricultural production without increasing its share of water, better mobilization of available resources and improvement of water-use efficiency are critical. These issues are now foremost in national development plans.

The dilemma is how to increase agricultural production with the little water available. Consumption levels of 2000 are taken as a reference, which should not be exceeded. Another challenge is how to ensure equity in water allocation. Access to water should be given to all those who need it. In arid environments, no crops can be grown without irrigation; while in semi-arid regions, farmers need irrigation to ensure more dependable yields.

Traditional options based on full irrigation with intensive cropping systems are probably no longer sustainable considering the actual constraints, investment costs and likely environmental degradation. In contrast, practices such as supplemental irrigation and regulated deficit irrigation have the potential to increase productivity and reduce environmental risks.

The objective of our study was to map areas suitable for developing supplemental irrigation from surface water. It involved two components: identifying potential areas for constructing structures to collect runoff water during the wet season; and developing a procedure to convert qualitative information about soils into a form suitable for irrigation ranking. Using commonly available data (rainfall records, DEMs and soil description maps), we were able to map areas potentially suitable for implementing supplemental irrigation cropping systems.

However, actual development of such systems will require more knowledge and sophisticated management. For optimal use of the very limited rainfall in Mediterranean environments, farming systems will need to be very specific. Each region will need solutions tailored to specific local conditions in narrowly defined production environments.

Semi-intensive agriculture based on supplemental irrigation can be sustainable and profitable; the key is rainfall management. Optimizing water supply during the growing season can significantly improve water productivity at the plant, field and regional levels. Production systems, if they can buffer inter-annual variations, will help a huge number of small farmers to become more productive.

PART II : WATER HARVESTING POTENTIAL

1 INTRODUCTION

Aridity is a typical feature of North Africa, where millions of hectares of agricultural lands receive less than 250 mm of rainfall per year. In terms of volume, this precipitation represents a valuable amount of water. However, because it is distributed over a large area, most of the water is lost by evaporation.

Many studies have shown that direct loss from the soil surface can be reduced by building water harvesting structures to concentrate rainwater in areas where it could be apportioned for useful purposes. Trapping rainwater and enabling it to be stored in the soil profile, offers multiple benefits. A greater percentage of the available precipitation is used; it reduces water losses from evaporation and from runoff to salty lakes; increases crop production; and contributes to erosion control and landscape preservation.

Thus, agricultural productivity in dry areas can be improved through land management practices specifically intended to reduce direct evaporative losses from the soil surface. However, achieving this goal is not easy.

Successful water harvesting – or even identification of areas suitable for water harvesting – requires adequate information on various factors: hydrology of the proposed site, rainfall, soil, relief, local cropping systems and socioeconomic conditions. Monitoring and surveys are usually needed to collect the necessary information; but as we usually deal with large areas, the cost could be prohibitive. An alternative low-cost method for assessing potential for water harvesting will be of great value.

This report describes a methodology for first-hand assessment of areas suitable for implementing water harvesting systems. The approach uses currently available data and knowledge together with modern tools such as image processing and geographic information systems to map potential areas for water harvesting. It takes advantage of the available experience in Tunisia, which has a long and successful history of water harvesting.

The methodology was developed through a study in the arid region of southern Tunisia, where annual rainfall is below 250 mm. Using existing small hydraulic structures as a starting point, we used a ’bottom-up’ approach. Available information, supplemented with data from fieldwork conducted on a pilot area, were used to derive suitability criteria that could be applied to similar environments elsewhere in North Africa and West Asia.

A comprehensive understanding of social factors is a prerequisite to any successful implementation of water harvesting systems. Therefore, we sought to ensure spatial integration of socioeconomic data into the study.

2 WATER HARVESTING SYSTEMS IN TUNISIA

Water harvesting systems are considered quite effective for improving the well-being of rural communities in North Africa, where recurring deficiency of soil moisture is a critical problem, affecting crop and range production. The technique is based on the principle of concentrating low precipitation falling on a large area into a smaller area. The water collected is stored directly in the soil, in reservoirs, or in shallow aquifers for later use.

The local climate, topography and soil determine, to a great extent, the type and performance of the water harvesting system used.

2.1 Environmental context

Tunisia is exposed to the climatic influence of the Sahara and to mid latitude weather variations. The Atlas mountains, which stretch from Morocco to the Cap Bon peninsula in northern Tunisia, has a major climatic influence at the regional scale. Altitude, together with distance from the sea, determine seasonal and daily temperature amplitudes, air moisture contents and the overall local ecological conditions of vegetation growth and development.

The branch of the Atlas mountains, called Dorsale, oriented southwest to northeast, has a major impact on rainfall distribution. From Dorsale southwards aridity increases rapidly; the central area is medium to lower semi-arid, the southern region is under arid and desert conditions.

The main variate used to describe the multitude of Mediterranean bioclimates is the pluviothermic quotient of Emberger (Q), which is an empirical ratio calculated from measurements of rainfall, average minimum temperature of the coldest month (January) and average maximum temperature of the hottest month (July). Q values serve as guiding criteria along with the inventory of vegetation types to delineate the boundaries between different bioclimatic areas. On this basis, the limits of bioclimatic regions do not match with isohyets on climatic maps. Rainfall remains, however, the key factor that determines the overall water availability within a bioclimatic class.

In the traditionally rainfed farming regions, rainfall occurs in winter and normally the growing season for crops stretches between November and June to coincide with the rainy period. In areas where rainfall is lower than 250 mm, crops cannot be grown economically on precipitation alone without specific land management, including principally, water harvesting practices.

Rainfall variability is high both in terms of space and time and is accentuated with increasing aridity; the coefficients of variation are usually between 40 and 60%. Water harvesting has the potential to reduce risks associated with such erratic distribution, but this potential depends upon both hydrological and biological parameters directly related to the crop being grown. To make the best use of runoff water, characteristics such as rooting system and drought and flood resistance are important criteria for fruit trees. But for annual crops, the critical issue is how to optimize growth duration in relation to water supply.

Average winter temperatures are usually high enough not to stop vegetative growth completely, especially in areas exposed to the warming influence of the sea. Inland, development is slower during the cool season, reducing crop water-use efficiency; frost damage could be a risk at higher elevations.

The most feared threat is probably the hot dry winds, called *sirocco*, which can occur at almost any time of the year although with increased frequency as temperature and aridity increase. If *sirocco* coincides with the critical stage of crop growth, the effect could be devastating, particularly when soil moisture is not high enough to meet the sudden increases in water evaporative demand.

The number of practices involving the use of runoff water to supplement rainfall deficiencies is quite large. There are more than 25 techniques now in vogue in Tunisia. They vary according to a multitude of parameters, but all attempt to optimize the use of available water, soil and biological resources.

2.2 Major systems

Many water harvesting techniques, which make use of runoff as it is collected, have been operational for several hundred years. These include two related major techniques of micro-catchments, locally known as *Meskat* in the central coastal area where the mean annual rainfall is around 300 mm, and *Jessour* in the more arid zones (150 mm).

Meskat cover about 300 000 ha in the region of Sousse, representing about 5 million productive olive trees (Amami 1984). The typical landscape is dominated by rolling topography and soils having sandy loam textures, good infiltration rates and high water retention capacity. The method involves basically a catchment area, and a smaller collection area in which olive trees are grown. The cultivated area is formed by one or several compartments bounded by earthen embankment and connected by spillways.

Over time, the effectiveness of this technique for flood control, recharge of the groundwater table and for developing sustainable agriculture has been improved. The *Meskat* system seems to represent an optimum integration of the natural resources in the area. Originally, the ratio between collecting area and infiltration area was frequently higher than 2, but this ratio has now dropped to about 0.7 as a consequence of population pressure.

The success of the *Meskat* system is related to: (i) the low slopes, usually 2-10%, but never exceeding 16%, (ii) the good infiltration rate, depth (more than 1 m) and holding capacity of the soil, (iii) the good rooting system of the grown olive trees, and (iv) the use of the runoff area for grazing, which improves farmers' income.

The rationale for growing olive trees in such a system is their high adaptation to drought conditions and the possibility of using the biomass as green fodder. The biological cycle of olive trees takes place over two years and at different phases, shoot growth may respond positively to any rainfall event. Moreover, young buds may develop into flowers or into shoots depending on the soil moisture.

As for the social and institutional setting, the *Meskat* system has been developed mainly on private lands and embankments are designed so that all rainwater collected is kept within the farm. There is also a specific legislation that recognizes farmers' rights over runoff water.

The second major type, known as *Jessour*, covers about 400,000 ha (Amami 1984) of the arid mountainous area of southern Tunisia. It provides adequate control of runoff on steep slopes in areas where annual rainfall varies from 100 to 250 mm. The technique is based on the use of a large area with steep slope for runoff and the development of agricultural activities on the alluvial deposits. The water collection area consists of a series of terraces, so water can accumulate successively in several terraces as it flows downstream. Locally designed berms provide good protection of the cultivated area, prevent violent floods and ensure controlled use of the runoff water.

A runoff coefficient of 0.4 is considered as representative of the region, although values of 0.9 were observed in small basins. The ratio of catchment area to collection area varies commonly between 4 and 6 depending on the slope.

Another type of floodwater harvesting is practiced in regions characterized by 200-400 mm rainfall and very large watersheds and wide *wadis*. The objective is to divert all or part of the floodwater carried by *wadis* to neighboring cultivated fields for providing natural irrigation of crops. This artificial flooding system has three components: a diversion dam, a distribution network and cropped fields. The diversion dam is made of earth and acts as a fuse or safety mechanism that breaks if intense flood occurs. Modern structures are rather made using gabion and reinforced concrete. Distribution is through a hierarchical network: primary, secondary, tertiary canals, etc. Slope within the distribution network is quite low except at the partition points in order to avoid sediment accumulation. However, annual cleaning of such networks is recommended to remove accumulated silt. In some cases, there is no need for diversion structures, particularly for natural water spreading when gullies emerging from neighboring mountains feed directly the fields downstream. Flooding techniques are very effective for flood control and groundwater table recharge, especially in areas where irrigation from shallow aquifers is practiced.

In the sloping areas of the semi-arid, hill-reservoirs, terraces and embankments are the most common techniques used to enhance agricultural production.

All these techniques have been developed in Tunisia over many centuries. Comprehensive surveys of traditional hydraulic work in North Africa and specifically in Tunisia were carried out by Al Amami (1982, 1984) and more recent information can be found in Oweis et al. (2001) and Ben Mechlia and Ouessar (2004). The various water harvesting techniques are used in approximately 1 million hectares and help maintain agricultural production as well as social equilibrium.

2.3 Role of water harvesting programs

In the last few years, there has been a resurgence of interest in soil and water conservation practices. This was triggered by the need to protect the major watersheds in order to prevent flood damage, slow down sedimentation in the major hydraulic constructions and to trap water lost to the sea and to salty lakes.

The government has been supporting the costs of all conservation works with the active participation of farmers in the various programs as workers. In many situations, providing jobs, in areas with high unemployment, has become an important aspect of the soil and water conservation measures. Recent actions show the increasing importance of the social aspect. A number of lessons can be learnt from past experience.

There is common agreement that any soil and water conservation measures will be adopted only if they provide an economic advantage over existing conditions. A technique that poses too big a burden to the farmer, requires major change in working habits, and brings in too little profit, is likely to be rejected.

Scarcity and disparity of water resources make the basin management approach difficult to apply for water harvesting. The multiplicity of objectives to be met by the planned intervention, each trying to respond to a particular need in a particular region and defined by a given decision mechanism, would result in a multiplicity of techniques and thereby a diversity of management methods.

Agricultural aspects of water harvesting programs are very important and must be reinforced. But the attention of decision makers should not be diverted from developing appropriate management options based on participation of local communities, not only as agricultural workers, but also as partners in the process of making plans for the protection and use of natural resources.

Specific rules need to be developed as new areas are brought under water harvesting projects. Laws requiring the adoption of soil and water conservation practices by land users and prohibiting machinery and tillage equipment that destroy small hydraulic structures are examples of the legislation measures needed in the future. Also, individual farmers' rights over runoff water should be clearly recognized.

2.4 Characteristics of the *Jessour* and *Tabia* systems

Jessour are widely practiced in areas dominated by outcropping of calcareous formations and deposition of quaternary calcareous silt (loess). In Tataouine region (annual rainfall 100-150 mm) as many as 35,000 units have been implemented in about 100,000 ha at 400-600 m a.s.l. *Jessour* allow the concentration of runoff water so that crops on the target area can benefit from a water supply equivalent to 350-500 mm/yr.

Arranged in a series of contour ditches built on runoff watercourses, *Jessour* are mainly used for growing trees (Fig. 16). A single unit is made of three components: impluvium, terrace and dyke. The impluvium is the area which collects and conveys runoff water. During heavy rainfall events, a unit can also receive water from upstream units. The terrace or cropping zone is formed by artificial soil resulting from long-term sediment deposits; in some cases soil depth can reach 5 m. In general, fruit trees are grown on terraces (olive, palm, almond, fig), but legumes and cereals can also be planted in good years. In *Jessour*, the dyke acts as a barrier to hold back sediments and runoff water. Dykes are trapezoidal in shape, 15-50 m long and 2-5 m high, and are made of earth consolidated with a coating of dry stones to reduce the erosive effects of wave action of water on the front and back of the dyke. A central or lateral spillway as well as one or two abetments are used for emptying excess water. Spillways are

Figure 16. Water harvesting using Jessour allows extensive farming in arid regions with annual rainfall below 250 mm

made up of stones arranged in stairs in order to absorb kinetic energy of the overflow.

The *Tabia* structure is similar to the *Jessour*, but implemented in the foothills and piedmont areas where the slope does not exceed 3% and where the soil is relatively deep. The length of dyke is in the range 50-150 m and the height 1-1.5 m. The ratio of impluvium to cropped area in *Tabia* vary from 6 to 20. Like *Jessour*, *Tabia* also have a central or lateral spillway and two additional lateral bunds. Fruit trees and annual crops are commonly grown. A *Tabia* collects, on a cultivated area of 5% of the catchment, eight times the amount of each rainfall storm above 20 mm (Nasri 2002). *Tabia* are also an effective means to control soil erosion and improve groundwater recharge.

2.5 Pilot site

The study area, *wadi* Oum Zessar watershed, is located in the Medenine region in south-eastern Tunisia (Fig. 17). It has a total surface area of 336 km², divided into two sub-zones, an upstream and a downstream area, covering 220 km² and 116 km², respectively. Geodetic coordinates (UTM) of the site central area are: X=627550E, Y= 3698809N (Carthage datum), and its altitude ranges from 0 to 669 m a.s.l. The site has a Mediterranean arid climate with an average precipitation in the range of 150-230 mm/yr, and an average temperature of 19-22ºC.

The watershed is situated on the edge of two major geological landscapes, the Djebel Matmata, with a relief without vegetation where

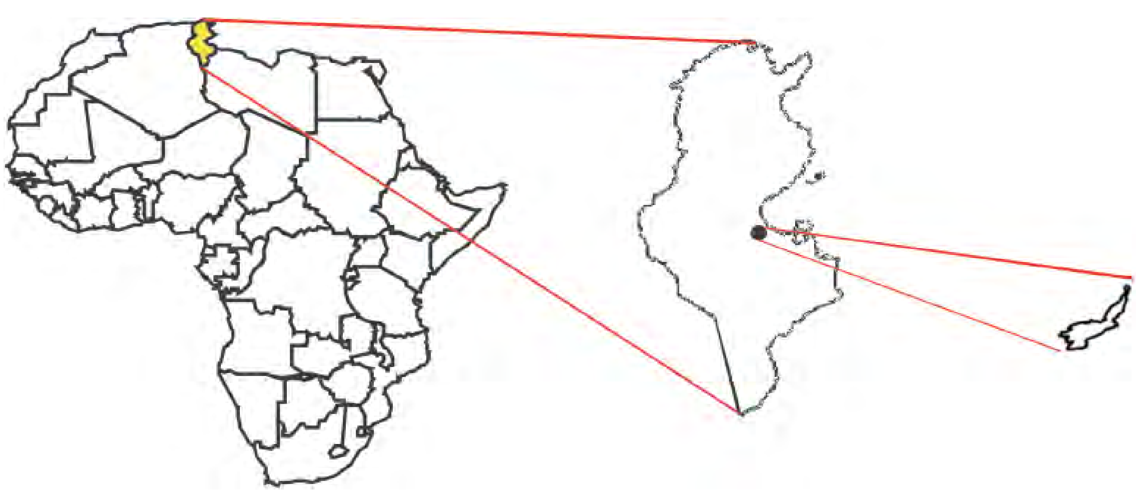


Figure 17. Pilot area of Oum Zessar used for developing the methodology for determining potential sites for water harvesting implementation in Tunisia

many slopes are totally bare as a result of wind or water erosion; and the Jeffara, located in the coastal plain.

Rangeland is the main land-use in the watershed area, with the steppe being the dominant vegetation. Four main ecological systems characterize the study site: Mountainous zone, Wadi beds and watercourses, Plains, and Saline area (Ouessar 2007).

Our study of the watershed covered 10 *imadas* (the smallest administrative unit in Tunisia) belonging to three counties. The total population of the watershed, according to the population census of 1994, is 24,188 inhabitants (5758 households, average family size 5.5).

A larger area covering the Zeuss-Koutine region was chosen for the development of socio-economic indicators. It covers approximately 1200 km² and includes Wadi Oum Zessar and other watersheds that start in the Matmata mountains and drain into the Mediterranean Sea. The basin is located between 33°15' and 33°40' north latitude and 10°06' and 10°35 east longitude.

The zeuss Koutine region faces strong pressure on its fragile natural resources, leading to high risks of desertification. The landscape is diverse, going down from the limestone relief of the Matmata chain, through the piedmont and glacis with loess deposits sensitive to water erosion, to the quaternary littoral depressions of the Jorf peninsula. The area is under the influence of the Mediterranean and Saharan bioclimates (with some rain in winter and none in summer). Average annual rainfall is low (100-200 mm), with a coefficient of variation exceeding 50%, resulting in a water balance deficit around the year.

Water resources are scarce and in most areas non-renewable. Surface runoff is collected mainly by traditional water harvesting systems for rainfed cropping (*Jessour*, *Tabia*) and domestic use (cisterns). New soil and water conservation structures are also used for groundwater recharge (Genin et al. 2006).

3 ASSESSING SUITABILITY FOR WATER HARVESTING IN ARID AREAS

Jessour and *Tabia* collect runoff water generated in the surrounding areas by small amounts of rainfall and store it in the soil. These structures are situated in gullies or in wadi tributaries. Sediments from the runoff accumulates at these structures, forming a deep soil substratum on which crops are grown.

Jessour are generally located in hilly areas where the slope is fairly steep, usually higher than 4-5% while *Tabia* are found in piedmonts and plains in areas with slopes under 3% (Ben Mechlia and Ouessar 2004). Since these systems are located on the hydrographic network and their location is influenced mainly by topography, flow accumulation and slope were considered as the basic parameters in our study.

The methodology aimed to optimize water supply during the wet season. It was developed in six stages:

i. Data correction
ii. Localization of existing *Jessour* and *Tabia* using Landsat and SPOT images
iii. Deriving a suitable flow accumulation range
iv. Deriving a suitable slope using DEM (SRTM and isoline-based DEM)
v. Defining suitability according to flow accumulation and slope
vi. Mapping water harvesting suitability in the pilot area.

3.1 Dataset

Two sets of data were used for the methodological development: (i) a dataset for the pilot area of Oum Zessar with high resolution and reliability was taken as reference. This dataset, acquired, verified and corrected during previous work, consists of 20-m resolution SPOT 5 image, 30-m resolution DEM, land use map (Fig. 18) and the watershed and hydrographic network (Ouessar et al 2003). (ii) commonly available data consisting of the 92-m SRTM DEM and a Landsat ETM image.

The Landsat ETM image was reprojected from UTM WGS 84 to UTM Carthage Datum, after verification with the 1998 SPOT image. It was shifted to correct for distortion. The obtained image has an RMS less than 1 pixel and visually it was coherent with the 1998 SPOT image.

DEMs of 30 m and 92 m resolution were used to generate the hydrographic network (HN). The hydrographic vector network was used as reference to assess the quality of DEM. Overlaying both hydrographic networks, minor discordance was observed for HN derived from 30 m DEM; while the use of 92 m DEM resulted in a network which had a systematic deviation from the reference due to conversion errors (shift in both directions, X 1 pixel and Y 2 pixels) and random errors associated with the quality of the DEM.

A burn-in operation of the DEM with the reference HN was used to correct these errors. To this end, the HN shape-file was converted to a grid file with the same resolution as the DEM and pixels belonging to the HN were coded with a selected number. A 5-m depth was used for the 30-m DEM and 5 m and 20 m were used for the

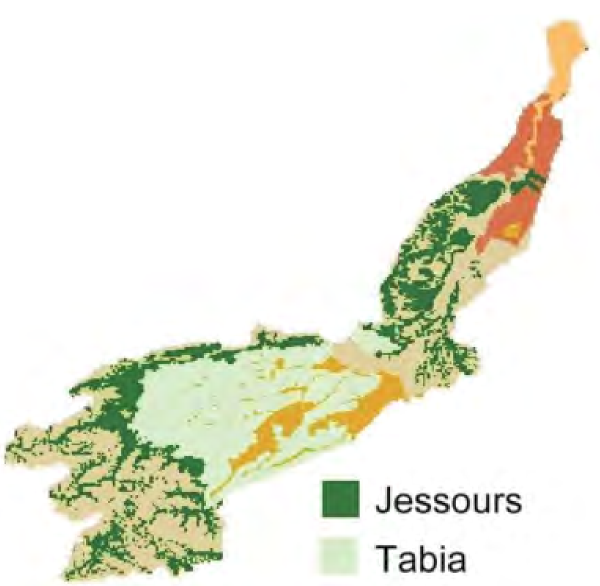


Figure 18. Land use map of Oum Zessar showing surveyed water harvesting structures

SRTM 92-m DEM. The resulting grid files were subtracted from the DEM using map calculator, and a sink-filling operation was performed.

3.2 Localization of existing *Jessour* and *Tabia*

The objective of this task was to localize and select a sample of *Jessour* and *Tabia* to be characterized in order to identify suitability criteria for these structures. The identification procedure used on the pilot-site of Oum Zessar watershed is summarized in Fig. 19.

A subset of the Landsat ETM scene which contains the pilot area of Oum Zessar catchment was extracted from the original image. Unsupervised classification with 50 classes was performed and visual investigation showed that vegetation covers corresponding to water harvesting structures are represented by three classes (9, 11 and 17).

Pixels corresponding to these classes were then extracted from the scene and considered as a vegetation map of the study area. This map was combined with the available land-use map to differentiate between *Jessour* and *Tabia*.

The SPOT image and the hydrographic network were used to check the accuracy of the classification process. Visual verification showed that most of the identified structures have a small size; they are represented by isolated pixels and are located in gullies. However, some errors of classification were observed: in some cases, large areas of several agglomerated pixels or small vegetation areas not corresponding to *Jessour* were classified as such. Considering that vegetation on water harvesting structures rarely covers large areas, a filter was used to discard all identified structures with areas larger than six contiguous pixels.

Flow accumulation and slope are the most important factors to be taken into account for implementing *Jessour* and *Tabia*. Impluviums with large area and/or slope that could generate too much runoff are a threat to the stability of the structure during important storm events, while a small area and/or slope which produces insufficient runoff water for plants grown on the structure may cause failure of the entire system.

3.3 Suitable flow accumulation range

The flow accumulation range favorable for *Jessour* and *Tabia* had to be determined using identified structures in the pilot area. However, even with the corrections applied to the DEMs, the stream network did not match perfectly with Landsat ETM and SPOT images, and some structures identified in these images were off, especially in narrow gullies. In order to link water harvesting structures to the stream network, a one-pixel (30 m) buffer was added to the DEM-derived contributing area grid after resampling to 30 m resolution. Three threshold values (2, 3 and 4 pixels) were tested for the best lower bound value of contributing areas.

An appropriate lower limit would produce the highest percentage of identified structures lying on the corresponding stream network. Several combinations were tried (Table 8) and best results were obtained for shifted and buffered flow accumulation maps with more than 2 pixels. For this combination, 92% of identified *Jessour* and 83% of *Tabia* were found on the hydrographic network. Consequently, lower bound value for both structures was taken as 2 pixels of 92-m resolution.

For the upper bound value, the presence of both isolated and clustered water harvesting structures on the pilot area makes it difficult to adopt a single threshold value. Clustered structures, identified as agglomerated pixels on the Landsat image, are associated with large contributing areas while small isolated structures are associated with small contributing areas.

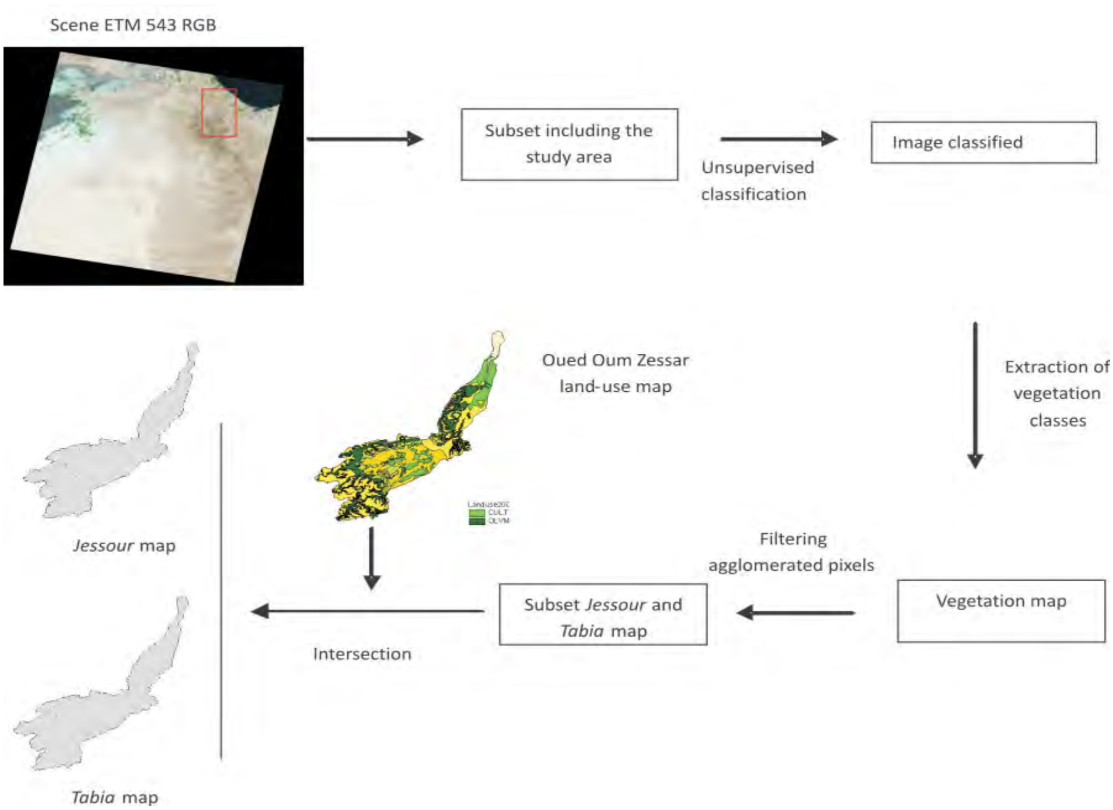


Figure 19. Procedure for localization and identification of Jessour and Tabia from Landsat image

Table 8. Percentage of identified *Jessour* and *Tabia* found on the hydrographic network for different combinations of corrections and lower bound values: 2, 3 and 4 pixels

	Jessour			*Tabia*		
Flow accumulation (92 m pixels)	4	3	2	4	3	2
Burned 5m	40	48	63	40	40	40
Burned 20m	43	51	63	40	40	55
Shifted	52	59	72	40	41	51
Burned 5m and buffered 1 pixel	65	74	87	65	71	84
Burned 20m and buffered 1 pixel	69	78	87	65	70	84
Shifted and buffered 1 pixel	76	83	**92**	40	70	**83**

An approach using statistical and visual verification was chosen to determine the best upper bound value of flow accumulation. Flow accumulation of all pixels within the *Jessour* and *Tabia* maps were determined and non-exceedance curves established (Fig. 20).

After investigation using stream networks corresponding to 90-99th percentile values and the SPOT image, it was found that some *Jessour* and *Tabia* were mis-classified. The value from which all structures identified on the SPOT image got off the stream network is adopted as the upper-bound limit for flow accumulation. A value of 114 pixels (approximately 100 ha) and 423 pixels (approximately 370 ha) were taken as the upper bound value for *Jessour* and *Tabia* respectively. They correspond respectively to the 92nd and 99th percentiles. Adoption of these values allowed us to exclude areas with higher flow accumulation.

3.4 Suitable slope range

The slope map is derived from DEM as a grid file where slope values depend upon DEM resolution and elevation. Low resolutions produce smooth slopes, high resolutions result in sharp slopes. In order to determine appropriate slope ranges to characterize isolated and/or clustered water harvesting structures, it was necessary to determine the aggregation level of DEM pixels over which slopes should be averaged. For this task, we adopted a straightforward method using aggregation of 30-m and 92-m resolution DEM and the land-use map based on field surveys to determine the best aggregation procedure and the range of slopes suitable for each water harvesting type.

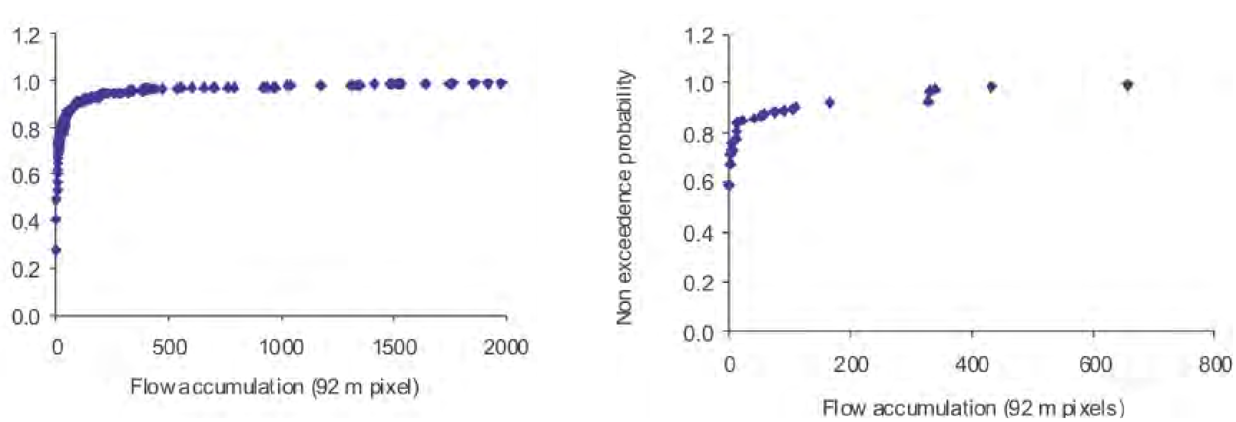


Figure 20. Non exceedance probability curve for flow accumulation in Jessour (left) and Tabia (right)

Within the reported area of *Jessour*, visual verification using the 30m resolution map revealed large variability of slopes. Some units located on large wadi beds have very low slope (<1%), while the slope of the immediate surrounding area being much higher. Adoption of lower resolution (92 m) reduced such contrasts.

It turned out that both resolutions failed to produce homogenous areas similar to the land-use map. Using lower resolution could smooth slopes and eliminate such heterogeneity. This can be obtained using two methods: averaging the high resolution slope map over a larger number of pixels or averaging elevation in the DEM and then deriving a lower resolution slope map.

Degradation of slope and DEM maps was performed by aggregating 92 m pixels to 3x3, 5x5, 7x7 and 9x9. Then the threshold values were determined by a classification procedure, starting with thresholds of 1% and 3%. As given in the literature, slope was classified into three classes 0-1%, 1-3% and 3-75%, corresponding respectively to not useful for water harvesting, suitable for *Tabia* and suitable for *Jessour*. An iterative process based on visual verification allowed selection of adequate resolution thresholds.

In the first procedure, slope maps were produced from DEM after degradation of the 92-m SRTM DEM to resolutions of 278, 463, 648 and 926 m (3x3, 5x5, 7x7 and 9x9 pixels). Overlay of resulting maps with the land-use map allowed us to gradually improve the threshold values. The best match was obtained for a 278-m resolution with threshold values of 0.4, 2.4 and 35%. The proposed slope classes are therefore set to 0.4-2.4% for *Tabia* and 2.4-35% for *Jessour*.

With the second approach, slope maps derived from 92-m SRTM DEM were degraded to resolutions of 278, 463, 648 and 926-m. A similar procedure was applied for the selection of resolution and threshold values. The best match was obtained for a 278-m resolution and threshold values of 1, 2.7 and 25% for not suitable, suitable for *Tabia* and suitable for *Jessour*, respectively. Slope classes could be set then to 1-2.7% and 2.7-25%.

The effectiveness of these procedures was checked using the *Tabia* and *Jessour* maps identified from Landsat images. The percentage of identified units falling in the suitable area was about 90% for both methods without significant difference (Table 9).

The method using degraded slope was selected for our work. The ranges 1-2.7% and 2.7-25% were adopted to derive a suitability map for *Tabia* and *Jessour* respectively (Fig. 21).

3.5 Deriving suitability for water harvesting structures

Potential area for water harvesting was obtained by combining suitability criteria of flow accumulation and slope. This task was performed using map algebra operations. Results obtained for *Jessour* and *Tabia* (Fig. 22) are coherent with the land-use map derived from field surveys.

Table 9. Percentage of *Tabia* and *Jessour* falling in the suitable area, established using degraded slope map and degraded DEM

	Degraded DEM	Degraded slope
Jessour	88%	89%
Tabia	90%	91%

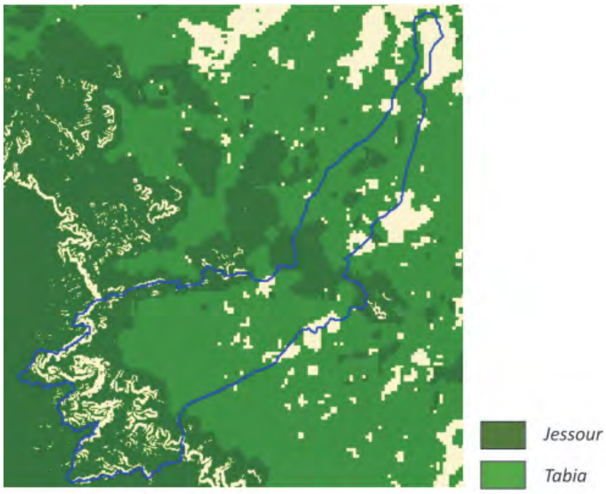


Figure 21. Suitability map for Jessour (dark green) and Tabia (light green) according to slope

4 INTEGRATION OF SOCIOECONOMIC PARAMETERS

Implementation and maintenance of water harvesting systems in a given area are governed by biophysical, social and economic factors. To assess the socioeconomic conditions of the farming population different scales should be considered. In this case, it is important to work at the basin or watershed level and the country level. Data available for a detailed analysis is at the basin level, but for the country level, information is available only for provinces.

This section analyzes the socioeconomic characteristics of farms in southern Tunisia, where water harvesting structures are commonly used. An attempt is made to identify information that could help define favorable socioeconomic conditions for water harvesting implementation and maintenance. Data from surveys at the basin and country level was used to characterize the socioeconomic conditions in areas where water harvesting systems are currently operational.

4.1 Spatial analysis of socioeconomic data

A comprehensive socioeconomic survey was conducted in the Zeuss-Koutine basin in 2002 which covers the pilot area of Oum Zessar and other watersheds (Sghaier et al. 2003). A total of 717 household heads were interviewed based on stratified random sampling taking into consideration structural variables (farm size, tree cultivation and livestock). All households were geo-referenced by GPS. Selection of variables for this study took into account the nature of data available at the national scale to allow exchange of results between different scales. Household data was averaged at the *imada* (smallest administrative division) level.

Using a frequency analysis method, appropriate class limits were set for the following variables:

V1: Population and household size

V2: Age of household head

V3: Education level of household head (high school and higher)

V4: Percentage of household heads active in agriculture

V5: Number of households with farm size less than 5 ha

V6: Number of households with farm made of more than 2 parcels

V7: Area under tree production

V8: Number of *Jessour* per household

V9: Percent of households practicing *Jessour* farming

V10: Number of *Tabia* per household.

Spatial analysis of the population data in the basin showed interesting distribution patterns:

- High presence of households owning *Jessour* in the steep upstream areas of the watershed (Fig. 23a).
- Farms where household members are involved in farming (more than 50%) are found throughout the basin (Fig. 23b). Important concentrations are also found in the upstream zones.
- Fig. 23c shows a contrasting distribution of household heads according to age. Household heads in the upstream and downstream ends of the watershed are generally older. Those in the piedmont are generally younger.

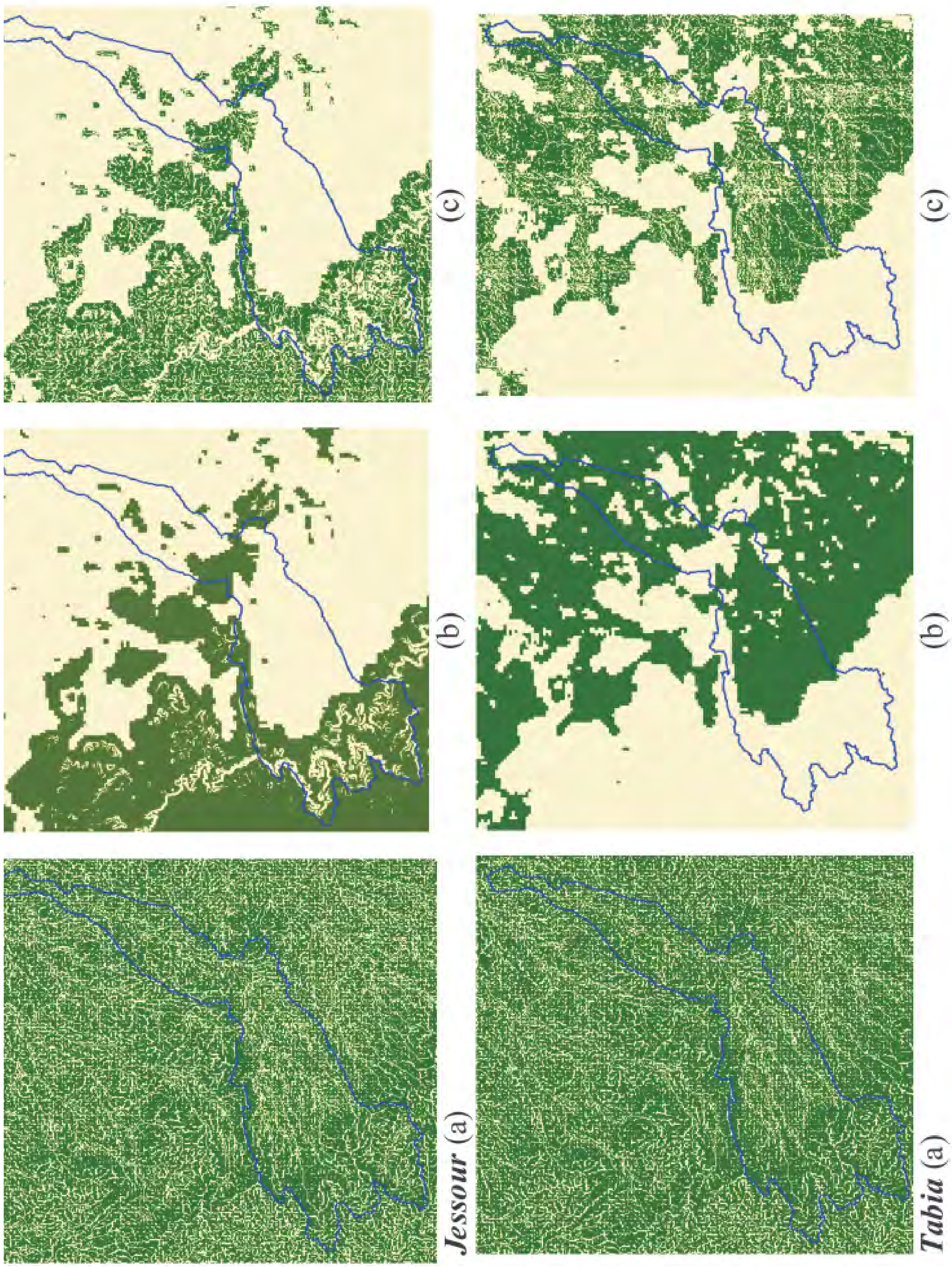


Figure 22. Potential for Jessour and Tabia in the study area (green color) based on(a) flow accumulation, (b) slope, (c) flow accumulation and slope

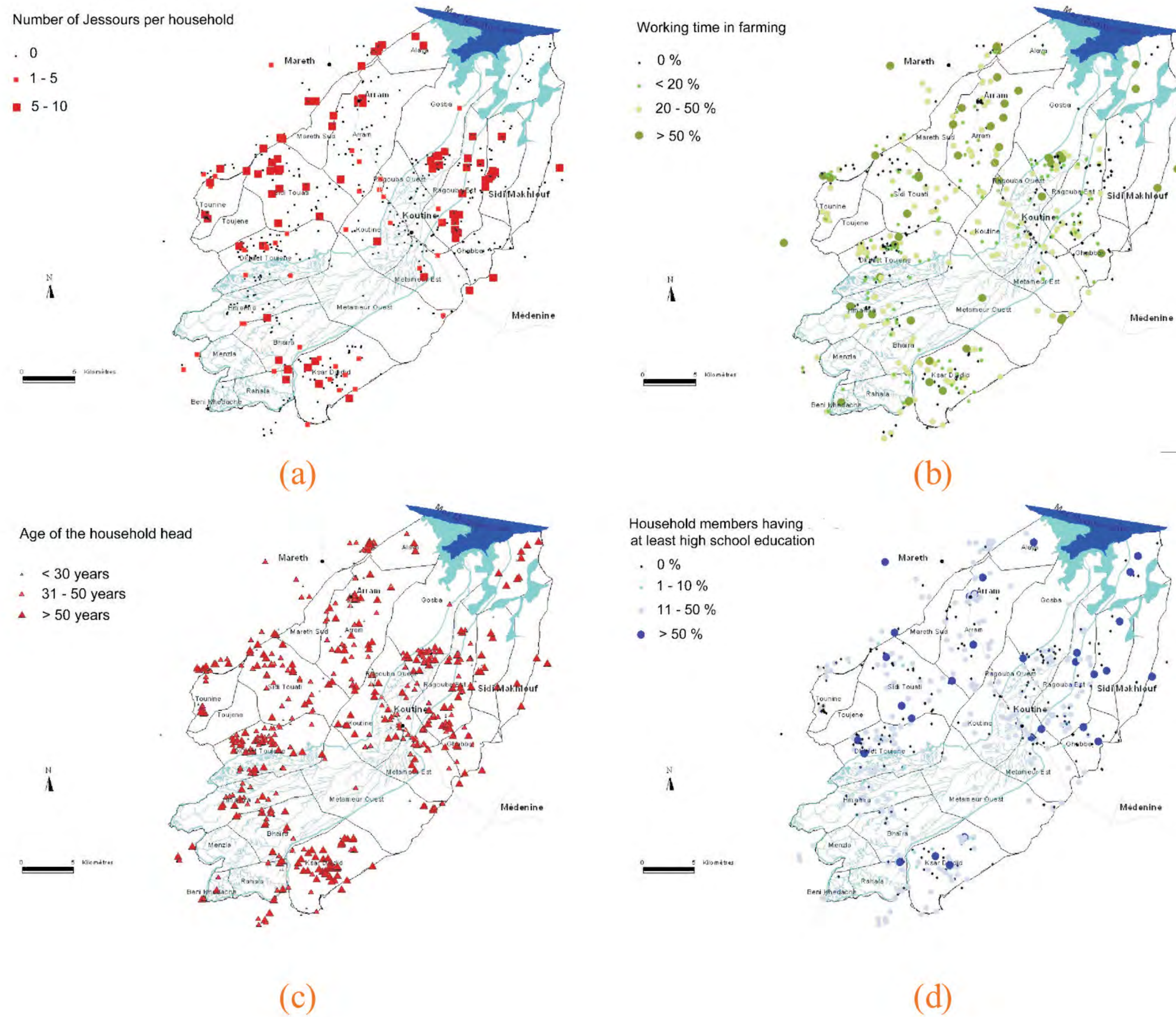


Figure 23. Spatial distribution (per household) of selected socioeconomic parameters in the pilot area

- It could be assumed that a higher level of education makes individuals more receptive to innovative ideas on water harvesting and more able to meet the ever-increasing cost of implementation and maintenance. Fig. 23d shows the percentage of household members with high school (or higher) education. Apparently, downstream zones have the highest proportion of educated people.

4.2 Aggregation and influence of socioeconomic parameters

To obtain a single indicator that could be used to scale out implementation of water harvesting, three socioeconomic variables are combined in this example: age, educational level of household members, and the percentage of working hours spent by household members on the farm. Statistical frequency analysis identified a 25% limit for these parameters as a basis for likely adoption of *Jessour* by a household. As a result, the following criteria were set:

- At least 25% of household members are younger than 40 years
- At least 25% of household members have high school education or more
- At least 25% of household members are active in farm work.

Correspondingly, households were placed in four classes, in terms of relevance of *Jessour* to their situation, and chances they would adopt this technique:

- Unsuitable: none of the criteria satisfied
- Slightly suitable: only one criterion satisfied
- Fairly suitable: two criteria satisfied
- Highly suitable: all three criteria satisfied.

The resulting distribution (Fig. 24) shows sites where implementation of water harvesting structures is likely to be successful, based on the socioeconomic hypotheses mentioned above.

Households responding to the highly suitable criteria are scattered over the entire watershed, however there seems to be a higher density in the upstream part of the watershed.

5 COMBINATION OF PHYSICAL AND SOCIOECONOMIC FACTORS

Our study first used biophysical characteristics to identify potential sites for the installation of water harvesting structures in the watershed (Fig. 22). We next considered socioeconomic parameters (characteristics of households, as described above) within these favorable areas. It was possible to integrate biophysical and socio-

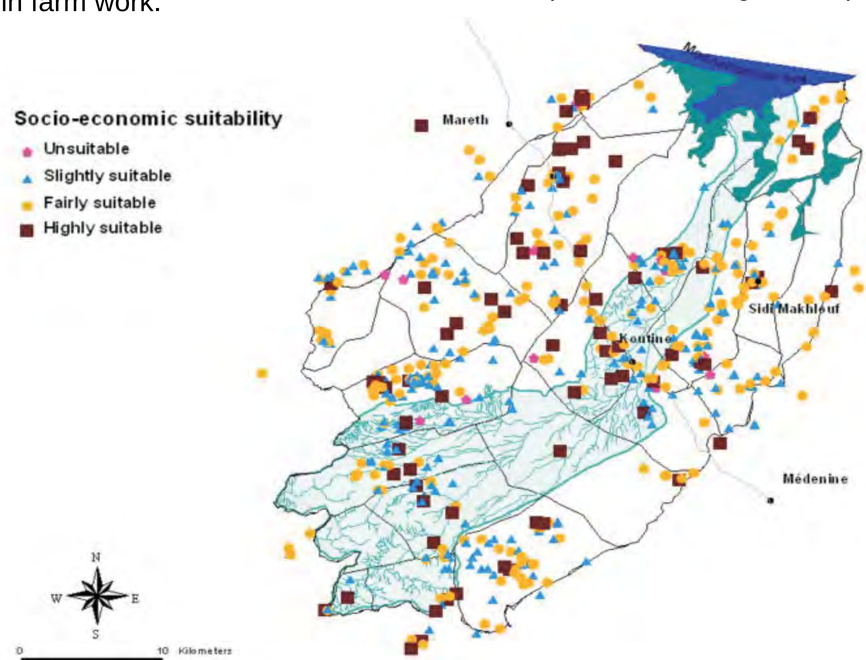
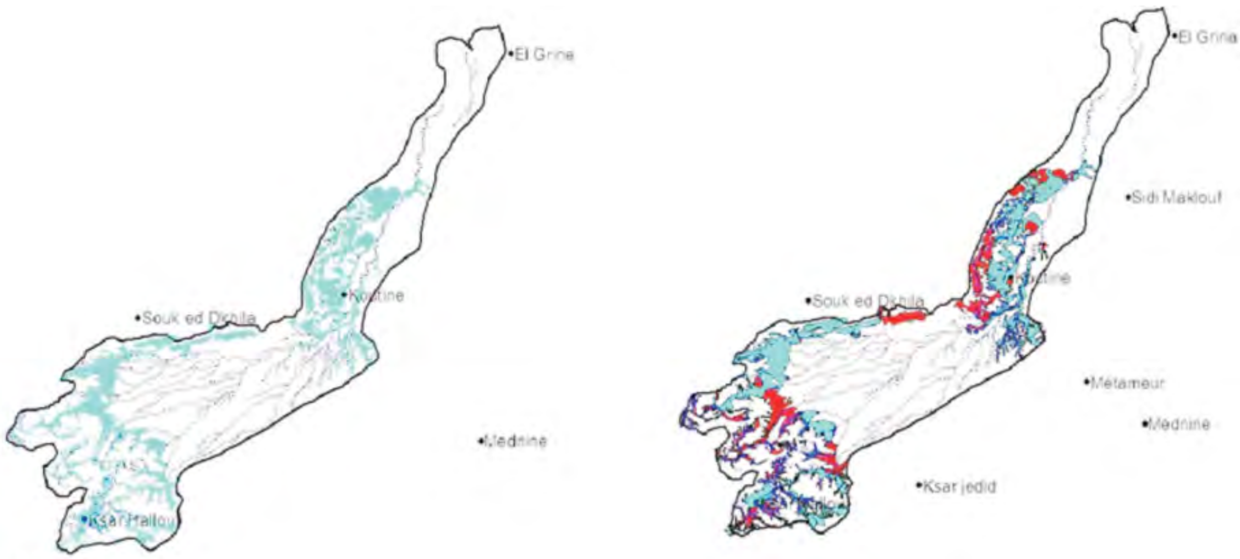


Figure 24. Use of socioeconomic suitability indicator for water harvesting development



(a) (b)

Figure 25. Potential sites for Jessour based on (a) biophysical criteria (in blue) and (b) narrowed down to areas with favorable socioeconomic conditions (in red).

economic parameters because spatially referenced socioeconomic data were available for the pilot area. Such data is not available at higher level. Interpolation of socioeconomic parameters was done by diffusing the density of points, using the spatial analyst extension.

Combining the suitability layer generated from biophysical factors with layers generated from the various socioeconomic parameters (age, education, etc) produced scattered potential sites where normally *Jessour* could be established successfully. As more factors are used in the selection process, the potentially suitable areas identified by combining biophysical and socioeconomic factors becomes smaller and more scattered. However, the most relevant combination was obtained with the '% active' criterion which is to be considered for any future expansion of water harvesting in those regions (Fig. 25). Apparently, structures cannot be maintenance unless farmers are present on the site. The effectiveness of the used method was checked by visualizing the obtained scatter of suitable sites and the actual *Jessour* distribution in the studied watershed.

6 CONCLUSIONS: WATER HARVESTING POTENTIAL

A flourishing agriculture was created in arid Tunisia through the development, over many centuries, of highly sophisticated soil and water conservation works. Although over-exploitation and lack of maintenance have caused some degradation, many water harvesting structures are still operational in different parts of the country. Government and other agencies are now making major efforts to rehabilitating these structures, and extending them to new areas.

We developed a methodology to identify, quickly and at low cost, areas potentially favorable for water harvesting, taking into account biophysical as well as socioeconomic factors. For reasons of practicality, the study was limited to two traditional techniques – *Jessour* and *Tabia* – which are widely used in the mountainous area of southern Tunisia, where annual rainfall is below 250 mm.

In the *Jessour* system, a large area with sufficient slope for runoff serves as the catchment; agriculture is practiced in the collection areas on alluvial deposits. *Tabia* are similar structures, but used in the foothills and surrounding plains in southern Tunisia. Our analysis showed that *Jessour* are used in areas with a slope range of 2.7-25%, and are able to collect water from a 100-ha watershed area. *Tabia* are used in areas with slope of 1-2.7% and require larger watersheds (370 ha) to generate enough runoff water to support long-term farming.

Water harvesting is concerned with the management of surface water runoff. Therefore, we first defined the physical conditions favorable to implementing the selected structures. This was based on com monly available spatial and climatological data, making the methodology easier to use, and widely applicable across the region. Identification of suitable sites for water harvesting requires adequate data on slope, catchment area and rainfall, as well as socioeconomic parameters. Planning, implementation and operation of the water harvesting system also requires a full understanding of social and land-ownership structures. A set of socioeconomic parameters have been considered (% active), instruction level (high school education) and age (<40 years). The best combination was obtained with the 'active' parameter, indicating that the presence of farmers is crucial for the maintenance of structures and the optimal exploitation of the collected runoff water.

In its entirety, a water harvesting system includes structures (e.g. small dams) as well as appropriate cropping systems and soil and water management practices. In dry North African environments, rainfall – although scarce and highly variable – is not the only issue. For instance, temperature is often a limiting factor for plant growth during winter. Temperature was not an important factor in our study, given the characteristics of the study area in southern Tunisia. But it could be important in other environments; in these cases more attention should be paid on how to better synchronize crop growth with water supply.

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