Conservation and Sustainable Use of Dryland
Agrobiodiversity of the Near East

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Water Harvesting Potentials in the Project Target Areas in Lebanon

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Introduction

Drylands in general are known for their within-species genetic diversity. The Levantine uplands, which comprise the eastern drylands of Lebanon, western Syria, and parts of northern Jordan and northern Palestine, are considered among the major centers of plant diversity and endemism in the world. Seven genera of vascular plants are endemic to this region. Many fruit trees like almond, olive, and pistachio have originated in the region and dominated its traditional agricultural systems. Moreover, the indigenous crops of the Near East are outstanding for their resistance to diseases and abiotic stresses. This makes them a valuable source of genetic material for germplasm enhancement upon which food security in the area depends (GEF/UNDP, 1999). Therefore, biodiversity conservation through sound natural resources management should be a national and regional priority.

The three target areas of the *Conservation and Sustainable Use of Dryland Agro-biodiversity of the Near East* project in Lebanon - Irsal, Nabha, and Ham – are all located in the northern marginal lands of the Bekaa valley which are semi-arid or arid in nature. These target areas are considered prime sites for the project due to their hydrologic characteristics, and the socioeconomic impacts this project can have on their farming communities. The elevations of the target areas range between 1100 m and 2700 m above sea level. The north Bekaa region is characterized by its dry hot summers and cold winters. The average annual precipitation, mostly in the form of snow, is about 300-400 mm in Irsal and Ham, and about 600-800 mm in Nabha.

Water scarcity is the main limiting factor against biodiversity in dry arid regions in general. Annual rainfall in arid regions is low relative to potential evaporation, and is hard to exploit because it is non-uniformly distributed over time and space. Most rainfall in such areas occurs sporadically with wide annual and seasonal variations. This variability is perhaps the most common and unpredictable problem that faces dryland agriculture and limits the possible cropping patterns and farming systems associated with it. Therefore, it has a negative effect on agrobiodiversity in arid and semi-arid areas.

Water harvesting has been used for thousands of years to supplement scarce water resources in arid and semi-arid regions of the world. In fact, water harvesting may help to mitigate the effects of water scarcity in dry areas. Rain water and snowmelt runoff can be collected in small earth reservoirs. The collected water can be stored for later use in supplemental irrigation. One application of supplemental irrigation during the growing season could be life saving for rainfed crops in dry arid lands. Moreover, the extended water availability during the dry season widens the farmers' choices among different cropping patterns and farming systems that can be used. Therefore, water harvesting can be considered as a key water resources management tool in any agrobiodiversity conservation scheme in dry areas.

Several researchers have worked on site selection of water harvesting reservoirs (e.g. Samra *et al.*, 1996; Srivastava, 1996; Gupta *et al.*, 1997; and El-Awar *et al.*, 2000). The site selection criteria in most of these references are based on soil and topographic suitability, land cover and land use, and surface runoff generating potential. Hydrologic modeling, remote sensing, and GIS techniques are usually used in the site selection processes of these reservoirs.

Methodology

Three field visits were done with a multidisciplinary team to the Project target areas. The main purpose of the visits was to conduct a preliminary assessment of the applicability of large-scale water harvesting techniques in different potential target sites of the Project. The visits were also useful in the agro-ecological zoning of the target sites. Several local farmers were contacted in each of the target areas to seek their cooperation and help in locating and visiting potential target sites within these areas.

Within each target area, several locations were assessed for their suitability as water harvesting reservoir sites. The preliminary assessment process was conducted with full participation of our local farmers/counterparts. The assessment criteria that were used in the process were adopted from the relevant literature through a participatory approach in which the local farmers played a decisive role. These criteria were based on the following characteristics of the potential sites:

- Land cover/use characteristics
- Surface runoff potentials
- Topographic characteristics
- Soil characteristics

The socio-economic dimension of site suitability for water harvesting reservoirs was implicitly considered in the preliminary assessment process within the land cover/use factor. This was done through the recognition of the local farmer land use preferences as well as the current land cover of the potential target sites. The local farmer land use and farming system preferences were positively correlated to their awareness of the positive impact of supplemental irrigation and water harvesting on dryland agriculture in general.

Field Visits

Nabha: Our main local guide in this visit was Mr. Nadim Amhaz, who works in farming and sheep herding in Nabha. Based on the potential site characteristics that were explained for him, Mr. Amhaz lead us through a field trip in which we toured about 12 potential sites within the vicinity of Nabha. The following potential target sites, listed in ascending order of their elevation, were visited: Kornet El-Qasr, El-Adhra, Kornet El-Halta, Kornet El-Hommos, El-Sawwaneh, Ras Wadi El-E'esh, El-Tnoubat, EL-Hamrat, Makyal El-Bohsa, Jowar El-Hajjeh, Kornet El-A'alyeh, Mashra'a El-Akhdar/El-Dahr (Appendix I).

Surface runoff and snowmelt tracks and traces become visible starting from El-Sawwaneh (1700 m) and above. Snow pack and current surface runoff start to become commonplace from El Hamrat (1850 m) and above. The topographic characteristics of most sites are suitable for small reservoirs. Moreover, some natural depressions are apparent in some sites that would be fit for water harvesting reservoirs with minimal excavation works (Figure 1). The prevalent soil types in the region are mostly reddish in color in addition to widespread patches of lime stone white rocks. The temporal and spatial non-uniform distribution of precipitation over the area has a magnified effect on the water resources budget in the region. The main agricultural source of income in Nabha is cereal production, which is exclusively rainfed due to the limiting availability of water in the area during the production season.

The preliminary assessment of the visited potential sites was based on the above mentioned factors and field realizations. As a result of this process, the following sites were considered as mostly suitable for water harvesting reservoirs:

1. El Hamrat (Figure 2)
2. Mashra'a El-Akhdar/El-Dahr (Fgure 3 and 4)

Both sites enjoy very good topographic characteristics. In fact, both are natural depressions at the foothills of several catchments that drain toward their direction. Most of these catchments were snow-packed during our visit to the area. Rainfed cereal production is apparent in the neighboring areas of both sites. On top of that, the land cover, soil, and topography of the vicinities of both sites tell that the potential for agricultural production development is significant in the area.

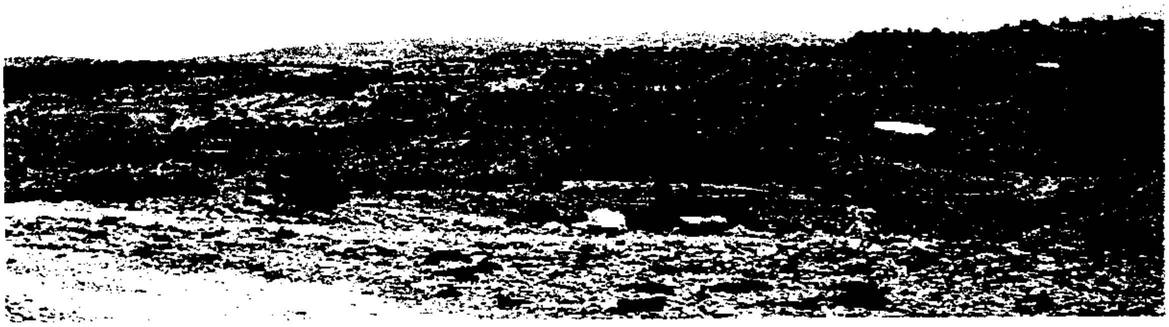

Figure 1: General view of Nabha target area.

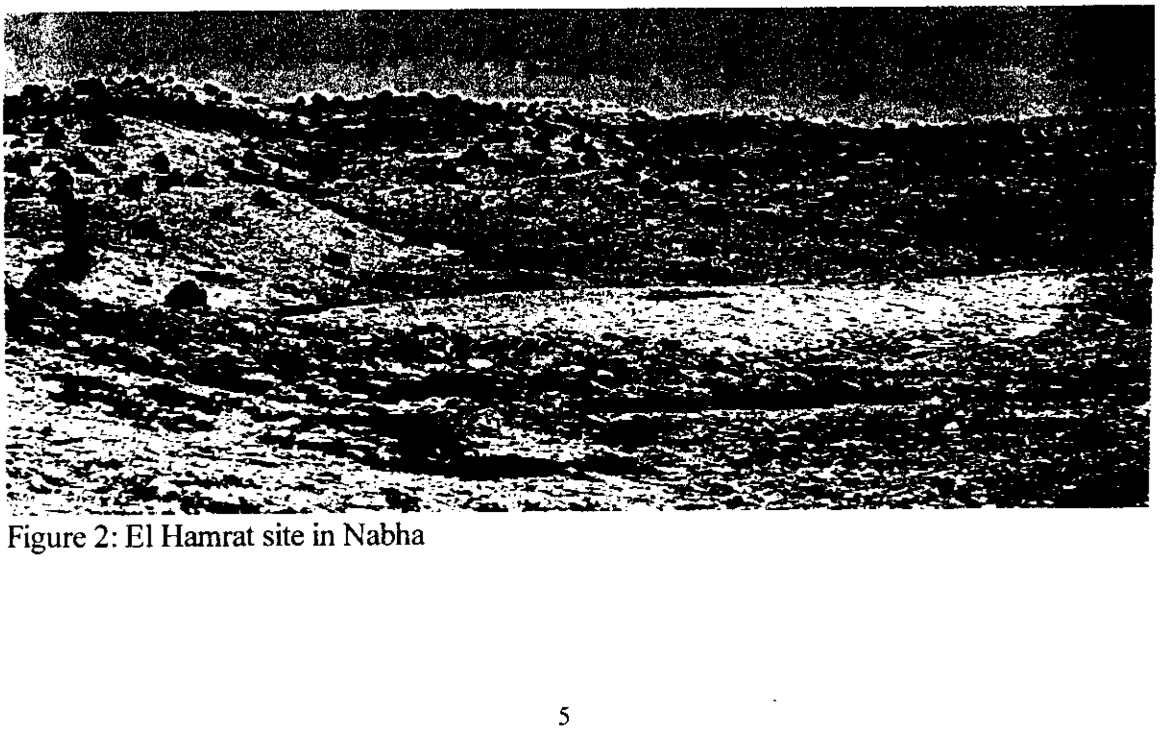

Figure 2: El Hamrat site in Nabha


Figure 3: Mashra'a El-Akhdar/El-Dahr site in Nabha


Figure 4: Closer view of the Mashra'a El-Akhdar/El-Dahr site in Nabha

Ham: Our second field trip was to Ham area. The local farmer who guided us in this field trip was the mukhtar of Ham Mr. Hussein Mrad. Before commencing with the trip, Mr. Mrad briefed us about the current status of agricultural production and main water resources in the area. He said that the main rainfed crops in the area are cereals and stone fruits, while major irrigated crops are apples, pears, and some annual field crops. He mentioned also that irrigated agriculture is fully dependent on groundwater supplies. In fact, we were informed about a lot of deep wells that had been drilled in the area since the early 1990's in a trend that is still going on.

It is obvious that such a trend will eventually lead to the mining of the groundwater reserves in the region. The occurrence of this scenario is very probable especially that there is no regulation or interference from any public sector agency for licensing and monitoring of well drilling, depth, and/or pumping flow rate. Therefore, the significance of water harvesting application in this area is double folded. On top of augmenting scarce water supplies in the area, water harvesting reservoirs would help in enhancing the recharging of the region's groundwater basins.

With respect to the field visits in Ham, Mr. Mrad led us in a tour on the potential sites for water harvesting reservoirs in the area. The visited target sites were the following: Wadi El-Mazra'a, Wadi Ain El-Zagha, Wadi El-Tyour, Wadi El-Houwwi, Oyoun Shnan, Wadi Ain El-Sawda, Wadi Ain El-Hajal, Wadi El-Kneeseh (Appendix II).

It is obvious from the differences in land cover types and density between the two areas that Ham is drier than Nabha in general. Nevertheless, tracks and traces of storm surface runoff and snowmelt can be found in most of the wadis and depressions of the area. Regarding land use characteristics and farming activities, rainfed agriculture is dominant in the vicinities of the visited sites. Making use of any additional amounts of "harvested" water in supplemental irrigation could be life saving for rainfed crops in some seasons. However, these signs of good potential for water harvesting application are damped by the heavy widespread presence of bare limestone rocks in the area. Storage capacities of water harvesting reservoirs could be severely affected by high risk of seepage losses in rocky areas.

The preliminary assessment of the visited potential sites for water harvesting reservoirs in Ham was based on the findings of the above-mentioned field trip. As a result of this process, the site of *Wadi Ain El-Zagha* was considered as the mostly promising for a water harvesting facility (Figures 5 and 6).

Figure 5: Site of Wadi Ain El-Zagha in Ham

Figure 6: Orchards that can benefit from a water harvesting reservoir in the site of Wadi Ain El-Zagha in Ham

This site is situated at the outlets of both Wadi El-Tyour and Wadi El-Houwwi. Consequently, it receives a relatively large amount of snowmelt and surface runoff water. Moreover, agricultural activity is easily traceable in the neighboring areas to Wadi Ain El-Zagha. The site also enjoys good topographic characteristics for building an earth water harvesting reservoir.

Irsal: The purpose of this trip was slightly different from the trips to the other target areas. This trip was done to acquaint the Project team with different agro-ecozones of Irsal (Appendix III) and to explain, in the field, the previous work that has been done on the assessment of water harvesting potential in the area. Our local partner in the area since 1993 has been the Arsal Rural Development Association (ARDA). Mr. El-Sayyed El-Fleeti among others worked very closely with us on this previous work that was published in El-Awar *et al.*, (2000) (Appendix IV). In the trip we toured the Wadi's as well as the Lower Jurd, Middle Jurd, and High Jurd regions of Irsal. Topographic characteristics, land cover types and cropping patterns, and surface runoff/snowmelt potentials in different agro-ecozones of Irsal were explained to the Project team.

The *Hydro-Spatial AHP* methodology for siting water harvesting reservoirs (El-Awar *et al.*, 2000) was explained in the field trip as well. This methodology for locating and ranking suitable sites for small water harvesting reservoirs was developed and applied to Irsal area that was selected as a representative pilot area of dry marginal lands of Lebanon. Hydro-Spatial AHP is based on quantifying the overall suitability for such reservoirs through a *Reservoir Suitability Index* (RSI) calculated for potential candidate sites. This index is developed using hydrologic modeling in conjunction with GIS and Analytic Hierarchy Process (AHP). Site attributes, related to different decision criteria, are determined through hydrologic modeling and GIS applications. The AHP decision procedure uses the calculated attributes in order to rank all potential sites based on their suitability for water harvesting reservoirs. The methodology excludes sites where reservoirs cannot be built, due to any physical constraints and/or restrictive land use policies, and ranks the rest of the sites based on their respective RSI values.

The results of the application of the Hydro-Spatial AHP methodology on Irsal area show that several sub-watershed outlets in the area are suitable sites for small water harvesting reservoirs. Most of these sites are concentrated in the High Jurd agro-ecozone due to the relatively high potential surface runoff and snowmelt values in this region. Currently the High Jurd region is predominantly occupied with rainfed stone fruit orchards that can benefit from the reservoirs through supplemental irrigation. This may lead to the introduction of new farming systems to the area. A wider choice of potential crops for the local farmers enhances the profitability and sustainability of agricultural production in the region.

Recommendations

Based on the findings during the field trips and later analysis of these findings, the following recommendations can be made regarding water harvesting potentials in the Project target areas:

- Water harvesting is one of the most important water management practices that can be done in the Project target areas. Building water harvesting reservoirs in the target areas would help mitigate the severity of seasonal water scarcity and, consequently, in the sustainable management of agro-biodiversity in these areas.

- Full assessment of the suitability of Nabha and Ham areas for water harvesting should be done. It is recommended to apply the Hydro-Spatial AHP methodology for siting of water harvesting reservoirs on both areas. This way the assessment would be based on a complete analysis of potential surface runoff, land cover, topography, and soil characteristics in the two areas. Such an application, which is way beyond the scope of this preliminary assessment, can be done at a later stage of the Project.

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APPENDIX I:

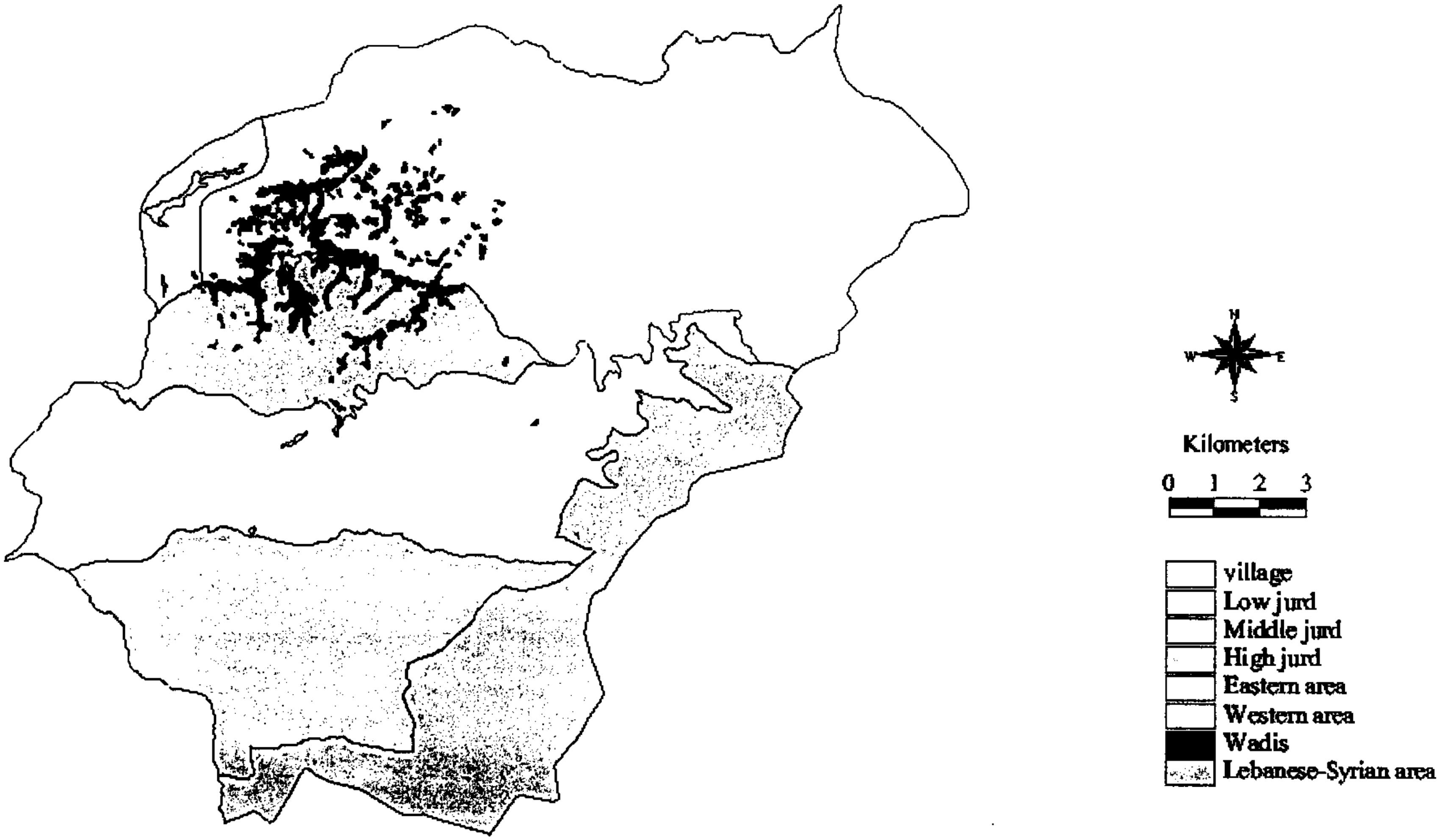
Map of Nabha

APPENDIX II:

Map of Ham

APPENDIX III:

Schematic diagram of Irsal area



Base map of Irsal

APPENDIX IV:

Copy of (El-Awar *et al.*, 2000)

criterion in the hierarchical ranking process of different candidate sites.

HYDRO-SPATIAL AHP

Hydro-spatial AHP developed in this work combines hydrologic modeling, GIS, and AHP techniques. Site attributes, related to different decision criteria, are determined through hydrologic modeling and GIS applications. Geographic Information Systems techniques are very useful for site selection studies due to its excellent capabilities in storing, analyzing, and displaying spatially distributed data according to user-defined specifications. Moreover, these capabilities are significantly enhanced by interfacing GIS and hydrologic modeling. Both techniques are used simultaneously for estimating the necessary spatial hydrologic parameters. The AHP decision procedure uses the calculated attributes in order to rank all potential sites based on their suitability for water harvesting reservoirs. Figure 1 shows a descriptive flowchart of the overall methodology linking hydrologic modeling and GIS techniques to the RSI development.

The Reservoir Suitability Index is based on a set of selection criteria defined by experts and discussed below. The methodology used for RSI computation can be represented by the following steps: (1) identification of selection criteria; (2) development of a hierarchy structure; (3) deciding on the relative weights of elements in different levels of the hierarchy structure; (4) determination of related site attributes through GIS and hydrologic modeling; (5) calculation of the RSI for all tested locations; and (6) ranking these locations based on the calculated values of their indexes.

SELECTION CRITERIA

The first step is to define the exclusionary and non-exclusionary selection criteria. The exclusionary criteria are used for initial screening that may result in excluding some tested sites from further analysis. Such criteria could be based on the presence of any physical constraints that prevent building a reservoir at a specific site, or on certain preset land cover and land use policies. The non-exclusionary criteria are those used to compute the RSI and to rank the sites that remain under investigation after the initial screening. The major non-exclusionary selection criteria are potential storage and land cover attributes of candidate sites.

Depending on how quantifiable they are, socio-economic factors considered in the site selection could be categorized under both exclusionary and non-exclusionary criteria. In this work, socio-economic factors have been mainly considered within the land use policy factors in the exclusionary criteria.

DECISION HIERARCHY STRUCTURE

The non-exclusionary criteria are arranged in a multi-level hierarchical decision structure and used to rank the non-excluded sites. The first level of this structure represents the ultimate objective of the decision process. The major non-exclusionary selection criteria are placed in the second level of the hierarchy structure. These major criteria may be further detailed and categorized into different sub-criteria and classes within subsequent higher levels of the structure. The highest level contains attributes or attribute classes that are determined through hydrologic modeling and GIS applications. Classification of attribute values into a finite number of classes would save on the

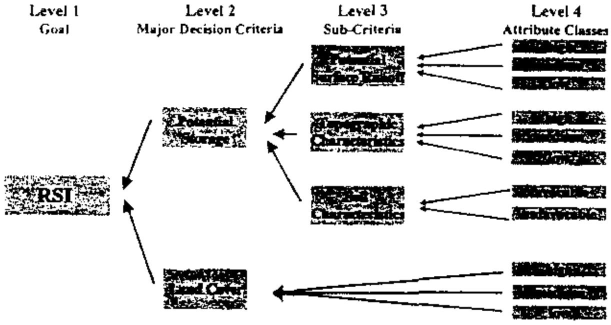


Figure 2–Decision hierarchy structure.

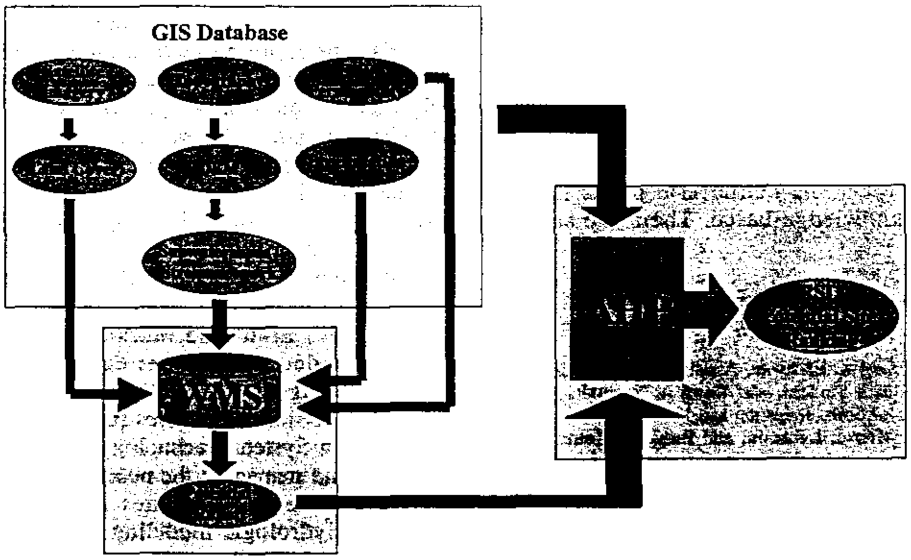


Figure 1–General flow chart of the developed method.

A HYDRO-SPATIAL HIERARCHICAL METHOD FOR SITING WATER HARVESTING RESERVOIRS IN DRY AREAS

F. A. El-Awar, M. K. Makke, R. A. Zurayk, R. H. Mohtar

ABSTRACT. *Water availability is the main limiting factor in dry-land agriculture, throughout arid and semi-arid regions, due to low annual rainfall depth and its non-uniform temporal and spatial distribution. Water harvesting has been used for thousands of years to supplement scarce water resources in dry areas. Surface reservoirs are used to collect and store precipitation surface runoff so that stored water can be used for supplemental irrigation during long dry seasons. This article presents Hydro-Spatial AHP, a method for siting small water harvesting reservoirs. This method is used to rank potential sites for such reservoirs based on a Reservoir Suitability Index (RSI) determined for each one of these sites. The RSI is calculated using Geographic Information Systems (GIS) along with hydrologic modeling and the Analytic Hierarchy Process (AHP). This method was applied to Irsal, a dry-land agricultural region in Lebanon. Results reveal that Hydro-Spatial AHP works well in that area. The article also shows the flexibility of the method with respect to the criteria used for ranking the candidate sites.*

Keywords. *Water harvesting, Geographic Information Systems, Hydrologic modeling, Analytic hierarchy process, Lebanon.*

Annual rainfall depth in arid and semi-arid regions is relatively low and hard to use due to its non-uniform distribution both spatially and temporally. Most rainfall in such areas occurs sporadically with wide annual and seasonal variations. This climate variability is perhaps the most common and unpredictable problem that faces dry-land agriculture and increases the risk associated with it. *Water harvesting* has been used for thousands of years to supplement scarce water resources in arid and semi-arid regions of the world. Moreover, it has recently received renewed attention because, in general, it is environmentally sound and easily integrated with indigenous and traditional knowledge (Samra et al., 1996).

Srivastava (1996) reported that site selection for small irrigation reservoirs is based on hydrological, topographical, and socio-economical considerations, and he cited several references on this issue (e.g., Palmer et al., 1982; Helweg and Sharma, 1983; Verma and Sharma, 1990). Carter and Miller (1991) and Cohen et al. (1995) worked on runoff reliability and assessment of risk associated with water harvesting in general. Vorhauer and Hamlett (1996) used a Geographic Information Systems (GIS) approach for siting cattle farm ponds that was qualitative and knowledge-based. Their site selection criteria included soil and slope suitability, current land cover and land use, and rain water harvesting potential in the area. Gupta et al. (1997) applied GIS and remote sensing techniques to develop a water harvesting strategy for semi-arid areas in India. They used the SCS curve number method for computing surface runoff, and they prioritized tested basins based on runoff generation potential, availability of agricultural land, and their suitability for constructing water harvesting reservoirs.

The general objectives of this research are to develop a methodology for locating and ranking suitable sites for small water harvesting reservoirs, and to apply this methodology to a selected pilot area in dry marginal lands of Lebanon. This method is based on quantifying the overall suitability for such reservoirs through a *Reservoir Suitability Index* (RSI) calculated for potential candidate sites. This index is developed using hydrologic modeling in conjunction with GIS and Analytic Hierarchy Process (AHP). The resulting method called *Hydro-Spatial AHP* excludes sites where reservoirs cannot be built, due to any physical constraints and/or restrictive land use policies and regulations, and ranks the rest of the sites based on their respective RSI values. Spatial AHP was developed and applied by Siddiqui et al. (1996) for preliminary landfill site selection using GIS conjunctively with the AHP decision making procedure. AHP, originally developed and introduced by Saaty (1979, 1980), has been widely used for quantitative assessment and ranking of alternatives (Cook et al., 1984; Erkut and Moran 1991). It has also been recommended by the United States Environmental Protection Agency (USEPA) to be used for comparing different decision alternatives (USEPA, 1993). Geographic Information Systems technology is used in this study for building and managing the needed digital spatial database to provide the site attributes required for the decision process. Hydrologic modeling is used to determine the potential runoff volume that represents a major decision

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efforts needed for the evaluation of large numbers of tested sites.

The hierarchy structure that is developed for this research is shown in figure 2. Its first level contains the Reservoir Suitability Index, which is calculated for all non-excluded sites. The major decision criteria that are used to calculate the RSI value are arranged in the second level of the structure. These criteria are the potential storage and land cover characteristics at the tested sites. In the third level, potential surface runoff as well as topographic and soil characteristics are assessed. These are the component sub-criteria that are used to evaluate the potential storage at the sites. Land cover attribute values are directly characterized with high, medium or low reservoir suitability without categorizing them into different third level sub-criteria. The fourth level, which is the last one, contains the attribute classes that are related to the major criteria and sub-criteria of the second and third levels, respectively. The values of these attributes are extracted from the developed hydrologic modeling and GIS approaches. These values are grouped into a number of classes based on value ranges of different selection criteria and sub-criteria.

RELATIVE WEIGHTS

Related selection criteria, sub-criteria, and attribute classes are compared to each other in pairs in order to develop relative weights (RW) for all elements in the hierarchy structure. All pairs of attribute classes that belong to the same sub-criterion are compared to each other. Experts qualitatively judge all classes for their relative weights in influencing the related sub-criterion in the neighboring upper level of the hierarchy structure. This qualitative judgement is quantified by fitting different degrees of preferences into a corresponding numerical scale. Table 1 shows the scale used to represent different preference degrees in this work.

A decision matrix is used for the comparison of pairs of attribute classes that belong to each sub-criterion. The degrees of preference of certain classes over the others are represented by their corresponding numerical values that fill the matrix cells. The decision matrices of all comparisons of attribute classes of level 4 are shown in tables 2a and 2b.

The above matrices provide a format for quantitatively comparing the weight or the importance of each attribute class, based on expert "preference" for this class, relative to other classes that belong to the same sub-criterion. The numerical values in the matrix cells represent the preference of one attribute class against another. For example, the first row of table 2a shows that high potential runoff level is preferred three times and nine times more than the medium and low levels, respectively. The last two rows of the same table also show that the preferences of the medium and low potential runoff levels are one-third and one-ninth of the high level preference, respectively. It is noted that the diagonal cells of the decision matrices are always filled with values of unity because they represent the self-comparison of attribute classes. The relative weight (RW) of an attribute class is determined as the normalized eigenvalue of the class row within the comparison matrix. The eigenvalue is calculated as the N*th* root of the product of all the elements of the class row, where N is the total number of elements in that row of the matrix. The computed eigenvalue is normalized by dividing it by the summation of the eigenvalues of all the rows of the matrix (Siddiqui et al., 1996). The decision matrices that represent the comparison of the major selection criteria and sub-criteria to each other are developed by the same procedure.

Therefore, the RWs of the fourth level of the hierarchy structure are based on the hydrologic, topographic, and land cover characteristics of the tested sites that are extracted from GIS and hydrologic modeling applications. However, the RWs of the other levels of the structure are not related to any site characteristics. They represent the relative weights of different selection criteria and sub-criteria in the hierarchical structure. Table 3 shows the RWs of the major criteria in two main scenarios that have been applied to test the developed method, and that will be discussed later in the article. Table 4 shows the sub-criteria

Table 1. Numerical scale for qualitative preferences

Degree of Preference	Corresponding Numerical Value
Indifference	1
Weak preference	3
Strong preference	5
Very strong preference	7
Absolute preference	9

Table 2a. Decision matrix for attribute classes of potential surface runoff, topographic characteristics, and land cover

	High	Medium	Low	Eigenvalue	RW
High	1	3	9	3.00	0.655
Medium	1/3	1	7	1.33	0.290
Low	1/9	1/7	1	0.25	0.055

Table 2b. Decision matrix for attribute classes of soil characteristics

	Favorable	Unfavorable	Eigenvalue	RW
Favorable	1	7	2.65	0.875
Unfavorable	1/7	1	0.38	0.125

Table 3. Decision matrix for major decision criteria (Scenarios I and II are described later in figure 5)

	Potential Storage	Land Cover	Eigenvalue	RW
		Scenario I		
Potential storage	1	5	2.24	0.833
Land cover	1/5	1	0.45	0.167
		Scenario II		
Potential storage	1	1/5	0.45	0.167
Land cover	5	1	2.24	0.833

Table 4. Decision matrix for potential storage sub-criteria (all sub-scenarios are described later in figure 5)

	Potential Runoff	Topographic Characs.	Soil Characs.	Eigen-value	RW
		Subscenarios I A and II A			
Potential runoff	1	5	9	3.56	0.693
Topographic characs.	1/5	1	7	1.33	0.259
Soil characs.	1/9	1/7	1	0.25	0.048
		Subscenarios I B and II B			
Potential runoff	1	1/5	7	1.33	0.259
Topographic characs.	5	1	9	3.56	0.693
Soil characs.	1/7	1/9	1	0.25	0.048

RW matrices adopted in two sub-scenarios that have been tested within each main scenario.

Site Attribute Determination

The site attributes related to different selection sub-criteria are determined through Geographic Information System (GIS) and hydrologic modeling applications. A GIS database is built for the entire tested area. Different data layers are used directly in computing the needed site attributes. The database is also used indirectly in this process by providing the needed input data for the hydrologic model to determine the potential surface runoff at the candidate sites. The determined site attributes are classified based on threshold values preset by experts. The developed site attribute classes are given their respective RWs that are used to calculate the RSI values at different sites.

RSI Computation

The Reservoir Suitability Index of a potential reservoir site is computed through the application of the following formula:

$$\mathrm{RSI} = \sum_{i=1}^{N_2} RW_i \times \left(\sum_{j=1}^{Ni_3} RW_j \times RW_k \right) \qquad (1)$$

where

RW_i = relative weight of level 2 major criterion i
RW_j = relative weight of level 3 sub-criterion j
RW_k = relative weight of level 4 attribute class k
N_2 = total number of level 2 major selection criteria
Ni_3 = total number of level 3 sub-criteria that belong to level 2 major criterion i

The above equation represents the ratings approach in the AHP decision process (Siddiqui et al., 1996). The relative weights (RW) of each group of level 3 sub-criteria are multiplied by the RWs of their respective level 4 attribute values, aggregated together, and multiplied by the RW of the corresponding major selection criterion of the second level of the hierarchy structure. This equation is applied to calculate the RSIs of all potential sites of water harvesting reservoirs. Ranking of the potential sites is based on the values of these RSIs.

Ranking of Potential Reservoir Sites

The computed RSI values are grouped into several classes, and the tested sites are ranked based on their respective RSI classes. Ranking the potential sites with respect to reservoir suitability helps in assigning priorities for different sites in the terminal stages of the decision process. The number and width of classes depend on the number and variability of individual RSI values. The final phase of this process consists of producing an RSI map showing the ranks of all potential reservoir sites under analysis. This map is produced as the final layer of the GIS built for the entire analyzed region.

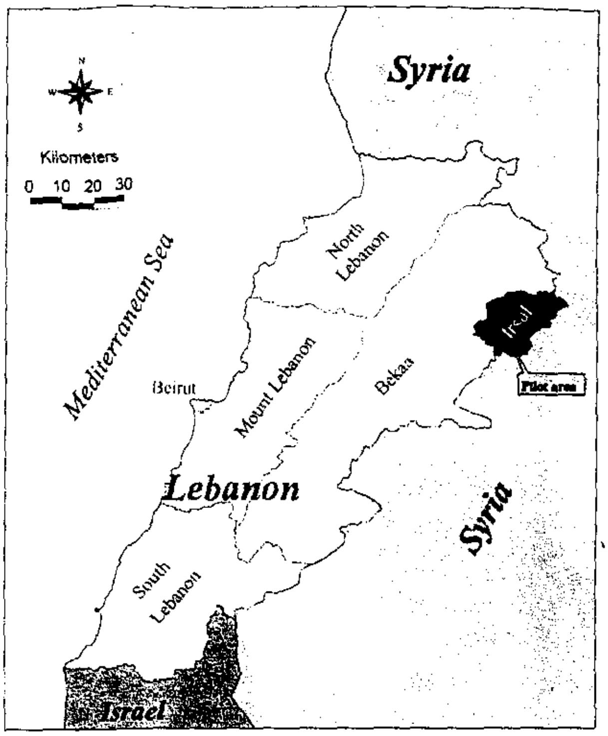

Figure 3–Pilot study area in Lebanon.

Application and Results

Pilot Study Area

This study focuses on Irsal, a remote Lebanese highland region located in the northeastern dry marginal lands of the western slopes of the anti-Lebanon mountain range (fig. 3). The region is characterized by its semi-arid weather with hot dry summers and cold winters. The elevation of the area, which faces the western border of the Syrian Badia, ranges from 1000 m to 2600 m above sea level, and its average annual precipitation is about 300 mm. This low precipitation depth, coupled with its temporal and spatial non-uniform distribution, has a magnified effect on the water resources budget in the region. The main occupation and source of income in Irsal is stone fruit production, which is exclusively rainfed due to the limiting availability of water in the area.

Water harvesting is expected to help mitigate the effects of water scarcity in the area. Rain and snowmelt surface runoff can be collected in small reservoirs and used for supplemental irrigation. One application of supplemental irrigation during the growing season could be life saving for rainfed crops in dry lands (Verma and Sharma, 1990). This may lead to the introduction of new farming systems to the area. A wider choice of potential crops for the local farmers enhances the profitability and sustainability of agricultural production in the region.

Data Acquisition and Processing

All spatial data presentation, manipulation, and analysis were done within a GIS that was built for the selected pilot study area. The ARCINFO/ARCVIEW environment was used to build the needed GIS and to develop, overlay, and analyze different data layers. The topographic-base map

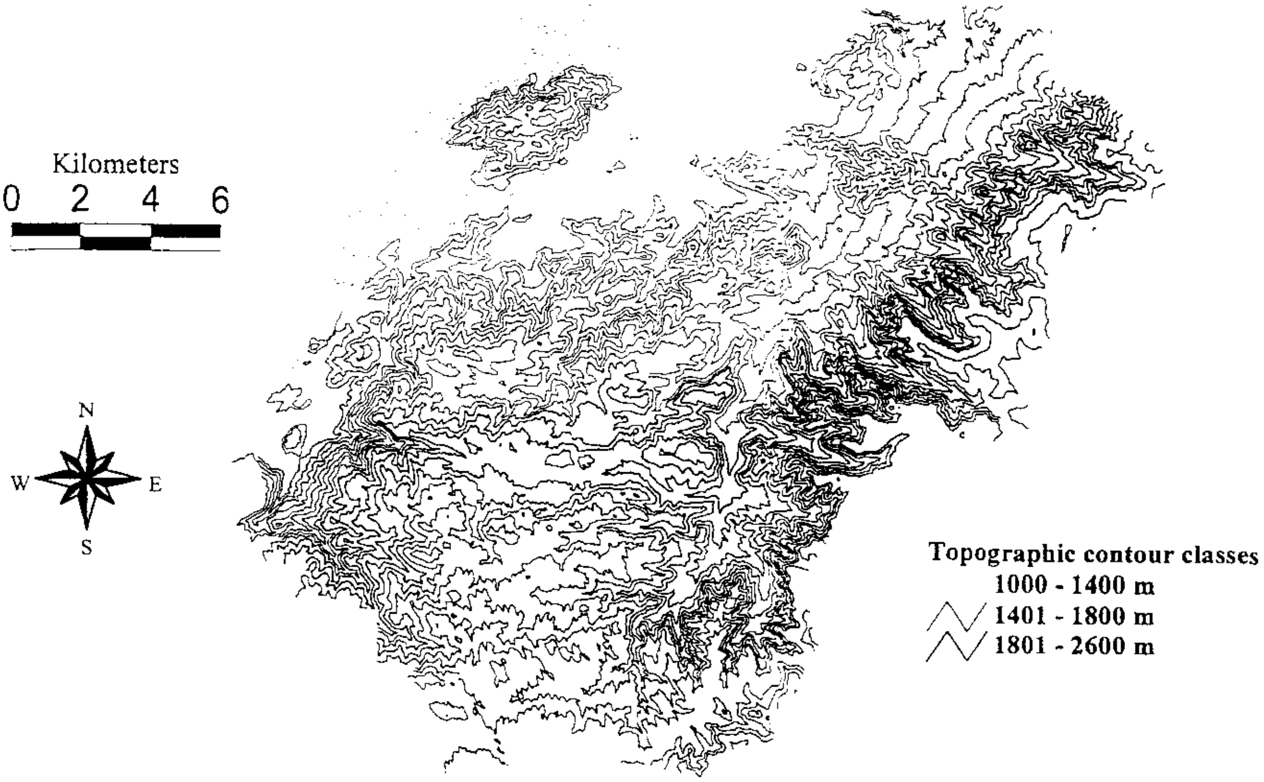

Figure 4–Irsal topographic map (40 m incremental elevation).

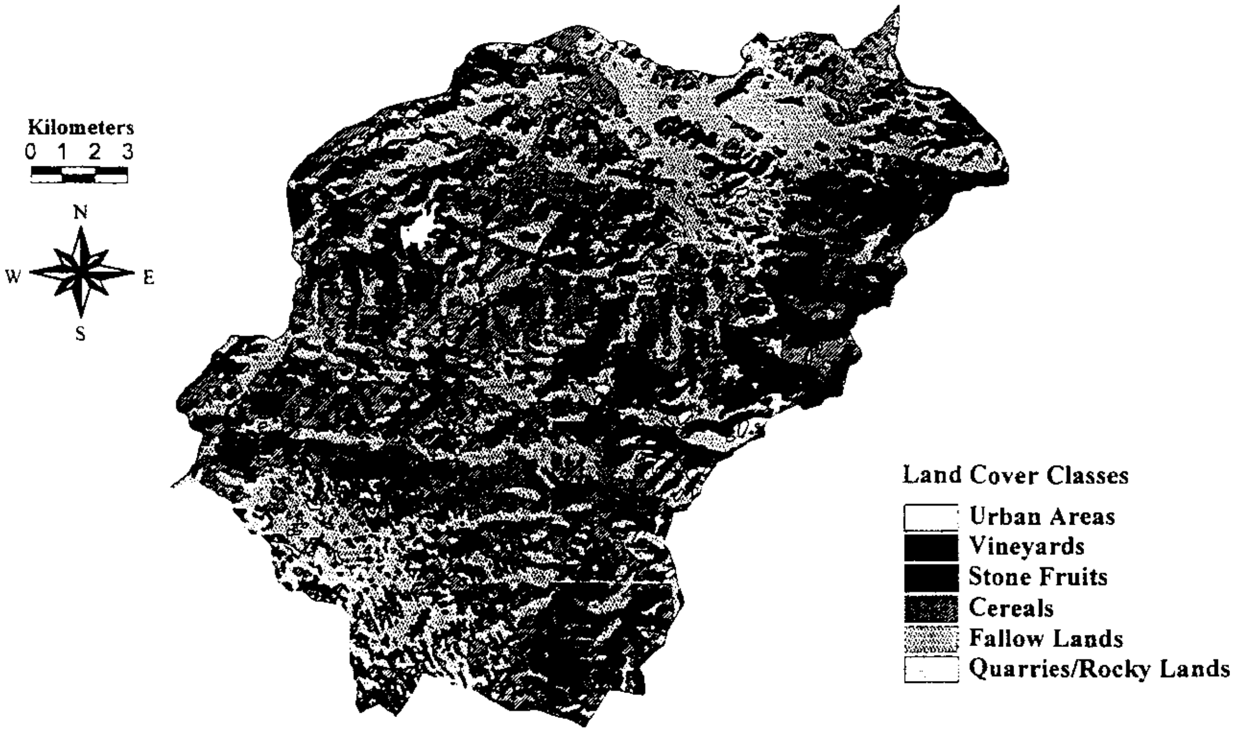

Figure 5–Irsal land cover (from SPOT satellite imagery).

(fig. 4) and the soil map of the area were digitized and clipped from existing hard copies. The land cover map (fig. 5) was developed from remotely sensed information. A SPOT (Systeme Probatoire pour l'Observation de la

Terre) multi-spectral satellite image for the area was ground-truthed and converted into an ARCINFO coverage. The sub-watershed map was delineated from the digital elevation model (DEM) that was built for the area using the hydrologic extension of ARCVIEW. Sub-watershed and stream network delineation was further edited and enhanced by on-screen digitization.

All sub-watershed outlets in the area were considered as potential reservoir sites and were tested for their suitability for that purpose. The needed hydrologic and basin parameters were estimated and extracted by applying the necessary queries on different layers of the GIS database.

DECISION CRITERIA

All decision criteria and their respective relative weights used in this work are based on indigenous knowledge and expertise in the pilot area as well as relevant literature (Verma and Sharma, 1990; Vorhauer and Hamlett, 1996; Gupta et al., 1997; El-Awar et al., 1998). Threshold values that define attribute class limits within the fourth level of the decision hierarchical structure (fig. 2) are selected on the same bases as well. An interactive participatory approach has been applied to make use of local farmers' experience to improve different criteria and attribute class limits extracted from the literature. Farmers actively participated in selecting the major criteria and their corresponding sub-criteria in the hierarchy structure. Farmers' knowledge and experience have been decisive in fine tuning the threshold values used for site attribute classification. Local expertise has also been heavily used in assigning the relative weights of different attribute classes in the hierarchy structure.

The exclusionary selection criteria used in this work for initial screening of potential reservoir sites are based on certain land cover attributes in the pilot area. According to these criteria, reservoirs should not be built in any existing stone fruit orchard because diminishing the agricultural area in the region defeats the purpose of this study. In other words, priority was given to the current land use for stone fruit production over its potential for water harvesting. Reservoirs also should not be located in any of the numerous rock quarries in the area. Deep seepage losses can be very high in these fractured limestone areas. Land cover and sub-watershed maps were overlaid and used simultaneously to determine the excluded sites from further consideration based on the above criteria.

After using the exclusionary selection criteria for the initial screening of potential reservoir sites, the non-exclusionary criteria were used within the hierarchy structure to calculate the RSIs of the sub-watershed outlets remaining under consideration. The land cover criterion in the decision hierarchy structure (fig. 2) represents the proximity of a potential reservoir site to stone fruit orchards and other agricultural lands in the area. In other words, this decision criterion assesses the potential site based on the need for water in its vicinity. The assessment is also based on the site's distance from its command areas and the associated cost of water conveyance. The criterion is not dependent on any third level components (sub-criteria) in the structure. It states that a potential site would be highly favorable when located within 50 m, and moderately favorable from 50 m to 150 m, from the closest farm boundary. Sites further than 150 m from a farm boundary would be characterized by low favorableness. These thresholds were chosen to keep conveyance cost within limits and to ensure the economic feasibility of reservoirs in this low input, marginal land, agricultural production area.

Potential storage decision criterion is composed of site topographic and soil characteristics, and potential runoff component sub-criteria. Potential surface runoff within individual sub-watersheds was estimated by means of the Soil Conservation Service (SCS) Curve Number Method (Soil Conservation Service, 1972). This method was selected for this work based on its use in the literature for similar purposes (e.g., Gupta et al., 1997), and due to its suitability for small rural watershed modeling in different climatic conditions (Chow et al., 1988). WMS (Watershed Modeling System), a comprehensive hydrologic modeling environment with GIS capabilities (BOSS, 1998), was used in this study. A composite (area-weighted) curve number was derived for each sub-watershed. The needed hydrologic and basin data were extracted from topographic, sub-watershed, and land cover GIS overlays that were imported into WMS and processed for that purpose. HEC-1 model (Hydrologic Engineering Center, 1990), interfaced with WMS, was used for runoff calculations. Due to the lack of storm data in the study area, daily rainfall data were processed and used. One representative year of daily rainfall data was used, and a Type I SCS rainfall pattern (Soil Conservation Service, 1973) was assumed to apply in the study area. Since the storm responses of different sub-watersheds relative to each other were more important than actual runoff values, using more than one year of rainfall data was considered redundant for studying the potential availability of surface runoff in the sub-watersheds of the area. Runoff volumes from individual storms were determined and summed up to estimate the potential annual runoff for all sub-watershed outlets. Based on their individual values, these potential annual runoff volumes were classified into high, medium, and low classes.

The topographic and soil characteristics sub-criteria are used in this study as indicators of the site potential storage capacity. Candidate sites with very steep or very mild slopes are considered to have relatively low storage capacities. Prevailing slopes of the tested sub-watershed outlets were determined from the topographic and sub-watershed digital maps. Slopes below 5% and above 20% were grouped in the low suitability class. Medium and high suitability classes were assigned to ranges of 5% to 10% and 10% to 20%, respectively. Soil characteristics classification was based on the sites' soil texture and clay content. The needed information was extracted from relevant GIS data layers, and two soil permeability classes,

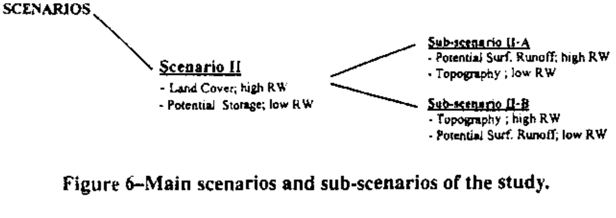

Figure 6–Main scenarios and sub-scenarios of the study.

favorable and unfavorable, were considered in the selection procedure.

RANKING OF POTENTIAL SITES

Two main scenarios with different relative weight (RW) combinations of decision criteria were tested in this work (fig. 6). In the first scenario, a larger RW was assigned for potential storage and a smaller one for land cover. The second scenario was used to examine the effect of swapping the relative weights of potential storage and land cover on the RSI calculations. Moreover, two sub-scenarios were considered within each main scenario with different RW combinations of potential storage component sub-criteria. The relative weights of potential runoff and topographic characteristics were exchanged in these sub-scenarios. The soil characteristics sub-criterion was consistently given the smallest RW in both sub-scenarios due to the relatively low variability of these characteristics throughout the pilot area.

In each sub-scenario, the RWs of the attribute classes developed from GIS and hydrologic modeling applications were used within the decision hierarchy structure, and equation 1 was applied to calculate RSI values for all sub-watershed outlets. Reservoir Suitability Index maps were created for all sub-scenarios of RW combinations. Figures 7-10 present the RSI maps that were developed for the four sub-scenarios. The maps show the excluded as well as non-excluded potential reservoir sites in the area. Four reservoir suitability classes, based on individual RSI values, were assigned for sub-watersheds of the non-excluded sites. The highly suitable class was given the first rank and the suitable, moderately suitable, and weakly suitable classes were given the second, third, and fourth ranks, respectively. The sub-watersheds of the excluded sites were ranked as non-suitable.

Figures 7 and 8 show the RSI maps of sub-scenarios I-A and I-B, respectively. Sub-watersheds with more potential storage are ranked under higher reservoir suitability classes due to the heavier relative weight given for this selection criterion in both cases. In figure 7 (sub-scenario I-A), preference for sub-watersheds with higher potential runoff is obvious due to the larger RW given for this sub-criterion. On the other hand, in figure 8 outlets of sub-watersheds with better topographic characteristics are consistently given higher RSI ranks. Results of sub-scenarios II-A and II-B are shown in figures 9 and 10, respectively. Outlets of sub-watersheds with more agricultural activity are given better RSI ranks in both sub-scenarios. Although potential storage is given a smaller relative weight in both cases, figures 9 and 10 show that swapping the RWs of potential runoff and topographic characteristics still affects the RSI calculation process and ranking of the candidate sites. Figure 11 shows the sub-watersheds whose outlets are classified either highly suitable or suitable (first and second ranks) in all sub-scenarios. These sub-watersheds are characterized by favorable land cover, high potential runoff levels, as well as good topographic characteristics. It is obvious that such sub-watersheds should be given first priority in any implementation program for building water harvesting reservoirs in the study area. In fact one of these sub-watershed outlets has already been selected by a local rural development association to build the first pilot water harvesting reservoir in the area (fig. 11).

The proven sensitivity of Hydro-Spatial AHP to the relative weight distribution of major selection criteria and sub-criteria is an extremely useful characteristic of this methodology. The sensitivity analysis uncovers important details about candidate site strengths and weaknesses with respect to specific decision factors. Having such details available, an analyst can have better understanding of the mechanism of the sub-watershed ranking process. In fact,

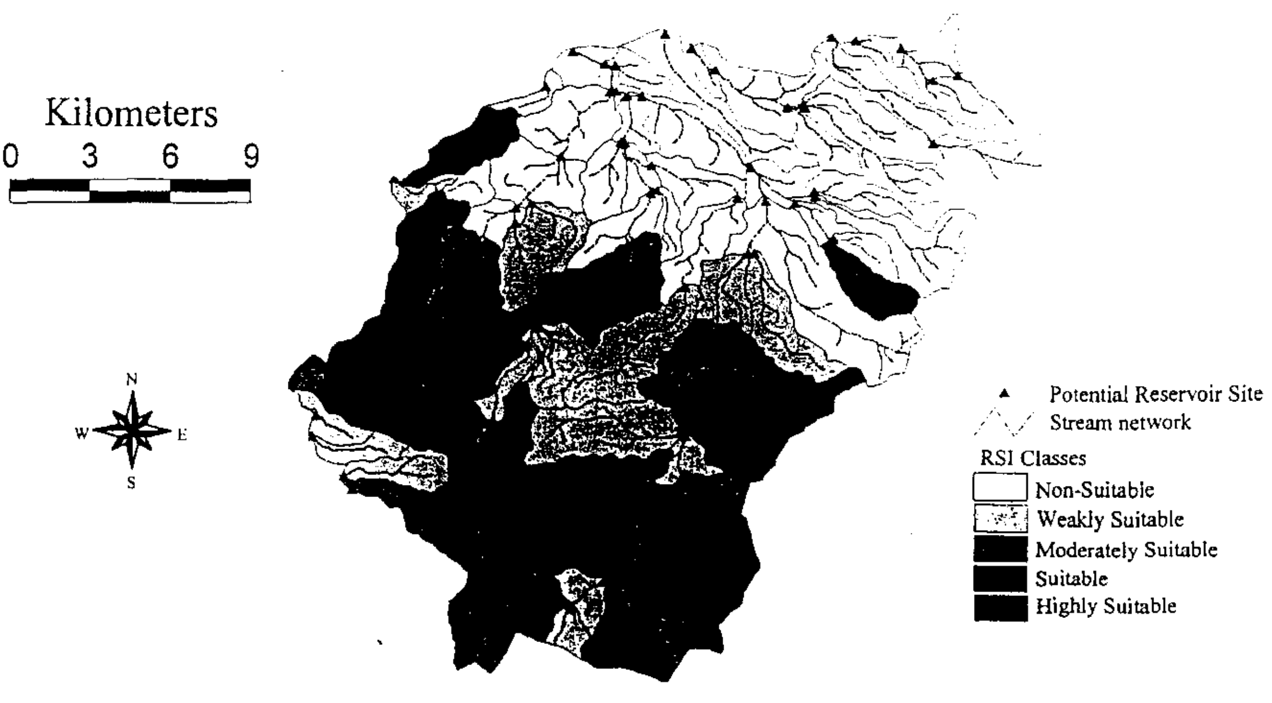

Figure 7–Reservoir Suitability Index (RSI) map — Scenario I A.

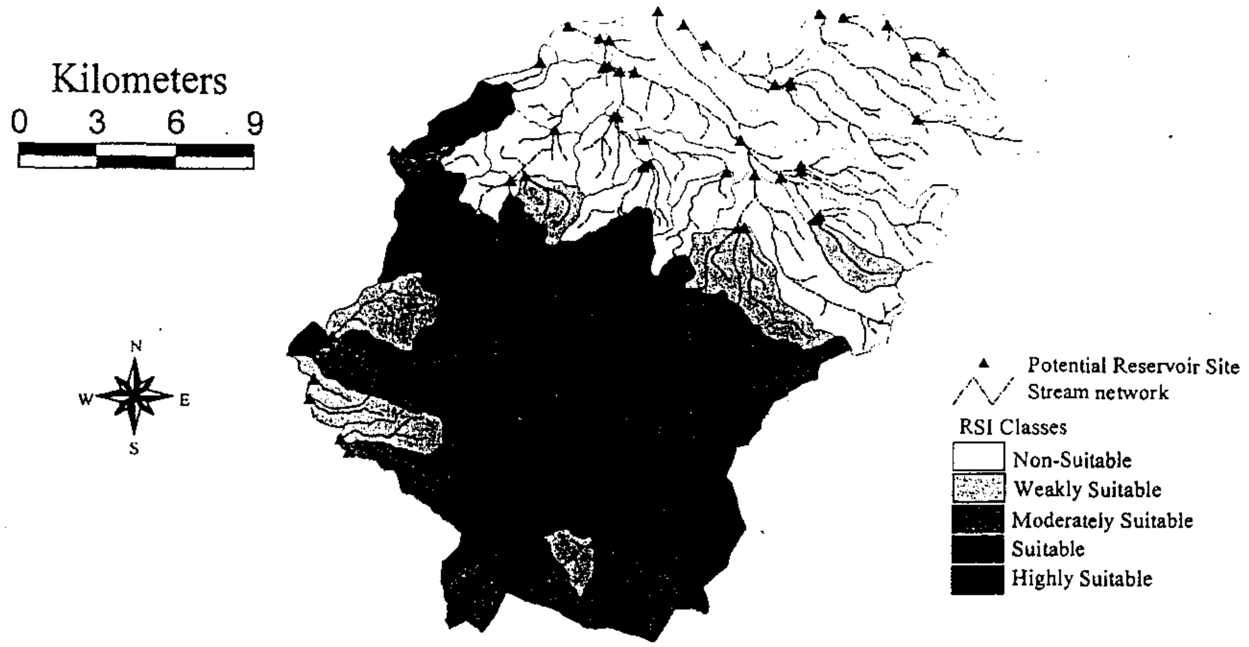

Figure 8–Reservoir Suitability Index (RSI) map — Scenario I B.

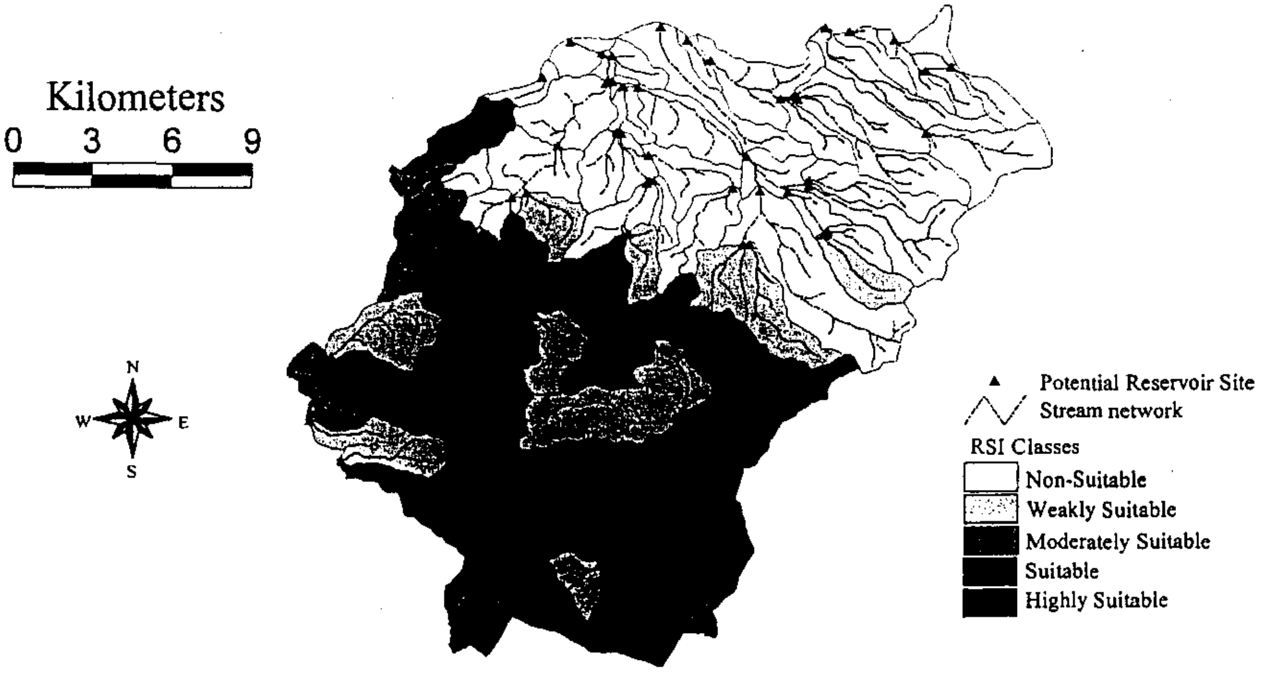

Figure 9–Reservoir Suitability Index (RSI) map — Scenario II A.

the analyst can explore and pinpoint the reasons behind giving a specific RSI for any candidate site. This would allow a decision maker to reach better informed decisions on the final selection of reservoir sites. It would also help in tracing the effects that any changes in sub-watershed land cover and land use might have on the decision process. This is especially important in the analysis of any site specific cases that may be faced in the ranking process.

CONCLUSIONS

The Hydro-Spatial AHP methodology for small water harvesting reservoir siting combines the capabilities of GIS, hydrologic modeling, and Analytic Hierarchy Process approaches. The application of the methodology in this work shows that it works efficiently for siting small water harvesting reservoirs. Moreover, the method is highly flexible regarding the number, types, threshold values, and relative weights of decision criteria on which the reservoir

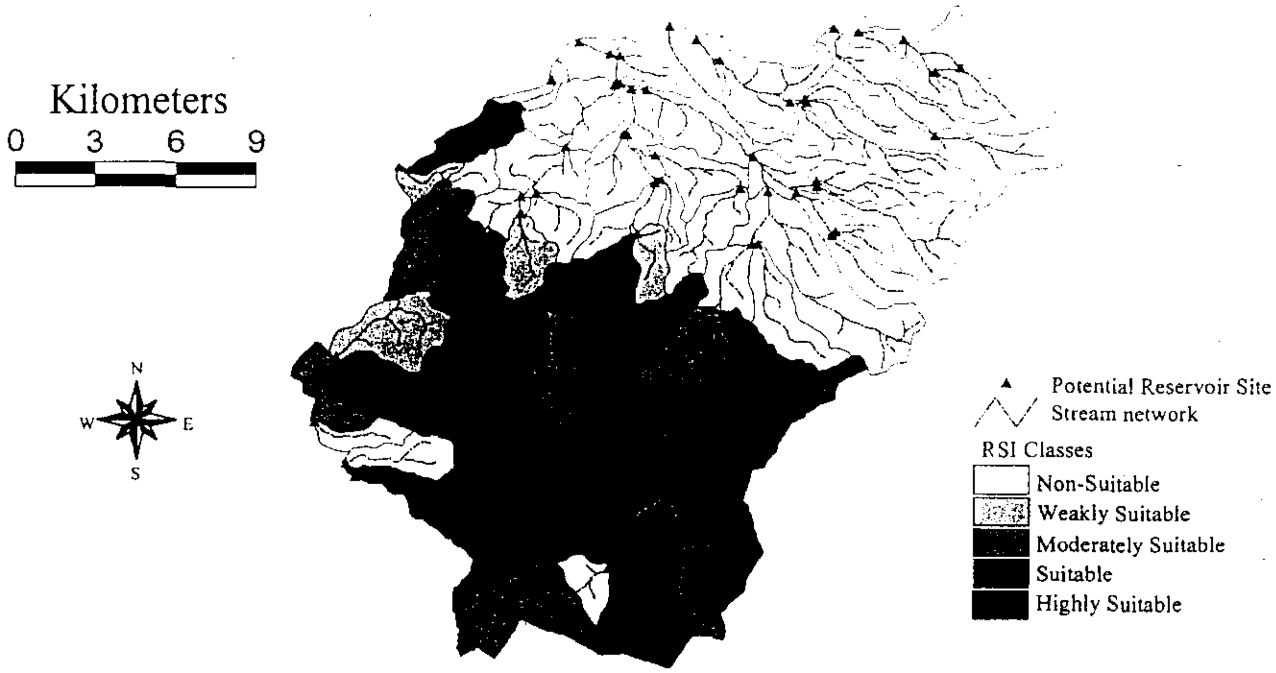

Figure 10–Reservoir Suitability Index (RSI) map — Scenario II B.

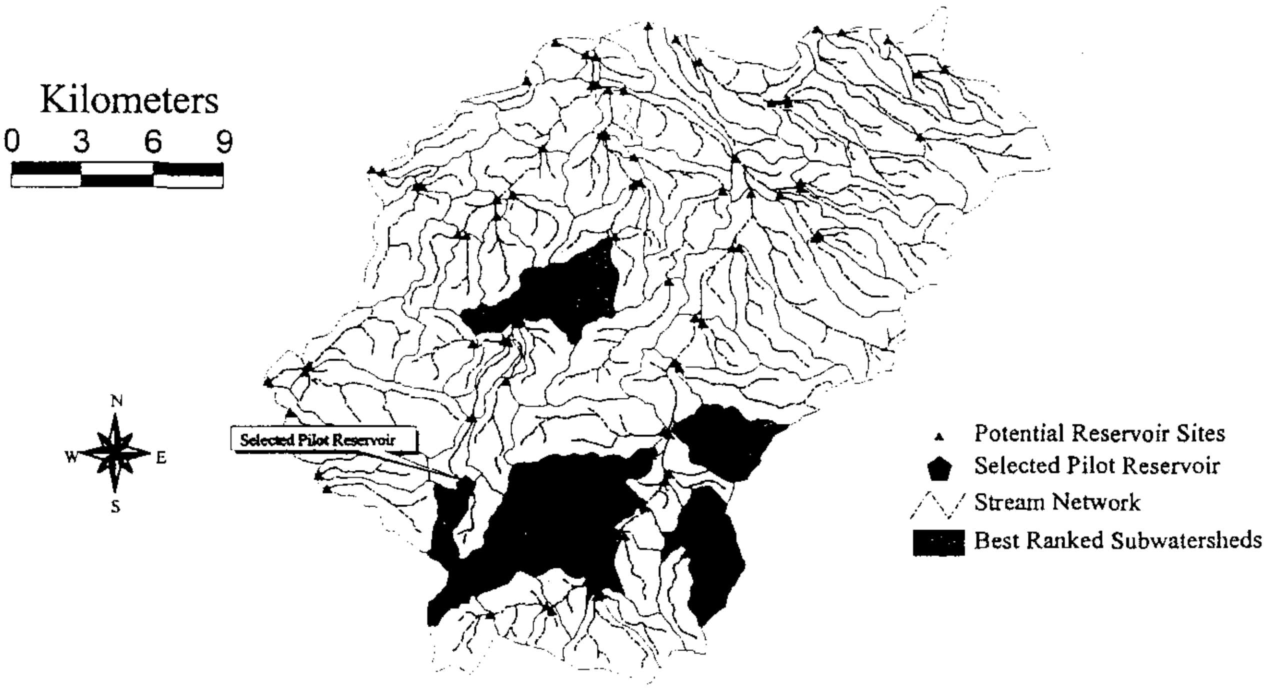

Figure 11–Best ranked subwatersheds common to all sub-scenarios.

siting process is based. The limiting factor against the use of any criterion is the availability of relevant digital databases not the method itself. The participatory approach that makes use of the local expertise and indigenous knowledge in developing the decision criteria and their relative weights could not have been used in this work without this inherent flexibility of Hydro-Spatial AHP.

The use of the same clearly defined hierarchical structure of decision criteria to rank all candidate sites insures the general objectivity of the methodology. However, the development of the criteria relative weights is based on subjective expert preferences. Therefore, special care should be taken in developing these RWs that should always be defendable and subject to cross checking. Moreover, the sensitivity of the method to the criteria RWs