GIS & ANALYTIC HIERARCHY PROCESS FOR SITING WATER HARVESTING RESERVOIRS

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Abstract

In this study, a methodology for siting water harvesting reservoirs was developed and applied in a 300 km^2 area of Irsal-Lebanon characterized by low and erratic precipitation to improve the agriculture potential. This involved development and application of a three-step Hydro-Spatial Analytical Hierarchy Process (AHP). First ArcGIS was used to produce pertinent spatial coverages. In the second step, Watershed Modeling System (WMS) was used to simulate the runoff in the watersheds. Finally, in the third step, a decision hierarchical structure using the AHP was developed and implemented to rank various potential reservoir sites according to their suitability expressed in terms of a Reservoir Suitability Index*. As a practical outcome of this study, a water harvesting reservoir was actually excavated at the outlet of the highest ranking watershed.*

INTRODUCTION

In this study, a water-harvesting reservoir siting methodology was developed as an approach for increasing the availability of water during summer months through supplemental irrigation. In a later stage, this methodology was applied to a selected pilot 335 km^2 area of Irsal in the dry marginal lands of Lebanon where recent plantations of rainfed cherry and apricot orchards are suffering from low fruit yield and quality.

MODEL DEVELOPMENT

Water harvesting planning usually consists of the following steps: 1) collecting needed data on hydrology, soil characteristics, land cover, and topography of the investigated area, 2) utilizing computer based analytical environment for data capturing, storage, manipulation, and analysis, 3) performing comprehensive hydrologic analysis of the investigated area based on collected hydrologic data and hydrologic modeling, and 4) using decision making tools for evaluating the different alternatives of water harvesting systems, including site selection and storage volume.

Hydro-Spatial Analytical Hierarchy Process

The study involved the development and application of a three-step Hydro-Spatial Analytical Hierarchy Process (HS AHP) for locating and ranking suitable sites for water harvesting reservoirs on the basis on the overall suitability of each reservoir.

The HS AHP used for reservoir siting is an extension and adaptation to the spatial-AHP methodology conceived by Siddiqui et al. (1996) to identify and rank potential landfill areas based on predefined criteria for preliminary site assessment.

The HS AHP integrates the following to select the highest ranking reservoir(s):

a) GIS,
b) Hydrological Modeling, and
c) AHP criteria

All criteria used in this methodology were integrated to yield the Reservoir Suitability Index (RSI) calculated for potential sites as a measure for the suitability of the corresponding reservoir.

The GIS Component

First, all spatial manipulations, analyses, and representations, were done within GIS that was used to produce pertinent spatial coverages. These included base, topographic, land cover and soil maps. GIS techniques are very useful for site selection studies due to their excellent capabilities in storing, analyzing and displaying spatially distributed data according to user defined specifications.

The Hydrological Modeling Component

In the second step, Watershed Modeling System (WMS) software was used to simulate the runoff in the watersheds. WMS is a comprehensive hydrologic modeling environment that uses a conceptual model approach. This model was selected primarily because it supports the Rainfall-Runoff model HEC-1 suitable when no runoff data is available as in the case of this study. It provides tools for all phases of watershed modeling including geometric parameter computation, hydrologic parameter computation, and analysis of runoff per outlet. The output would be a quantification of runoff at each outlet.

Two monthly conceptual lumped models that are not data intensive were then selected to compute the water budget (direct runoff, interflow, baseflow, snowmelt runoff and evapotranspiration) at the subwatershed level. These are Minrun and Wbudg and they are both developed through academic research and are still at the experimentation level. The modeling approach consisted of using HEC-1 generated synthetic runoff data as a substitute for the observed runoff data needed for input into both models. The models would then generate net direct runoff among other output.

The AHP Component

Finally, in the third step, a decision hierarchical structure using the AHP was developed and implemented to rank various potential reservoir sites according to their suitability for water harvesting. This method quantitatively assessed decision alternatives using GIS attributes and hydrologic modeling results in terms of a Reservoir Suitability Index (RSI). Six steps represent the methodology used for RSI computation.

Site attributes, related to different decision criteria, are determined through hydrologic modeling and GIS applications. Both techniques are used simultaneously for estimating the necessary spatial hydrologic parameters. The AHP decision procedure uses the calculated attributes in order to rank potential sites based on their suitability for water harvesting reservoirs.

i) The identification of selection criteria

The first step was to define the two non-exclusionary criteria. For the ‘hydrology and geology of the outlet’ factor, the three sub-factors the water budget, the topography and the soil type at the outlet were included. For the ‘land cover of the subwatershed’ factor, two sub-factors ‘the proximity to agricultural land’ and ‘the area planted in that land’ were included.

ii) The development of an adequate hierarchy structure

The selection criteria are arranged in a multilevel hierarchical decision structure. The first level of this structure represents the ultimate objective of the decision process, the RSI. The major selection criteria are placed in the second level of the hierarchy structure. These major criteria are further detailed and categorized into different subcriteria 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 efforts needed for the evaluation of a large number of tested sites. These are shown in Figure 1.

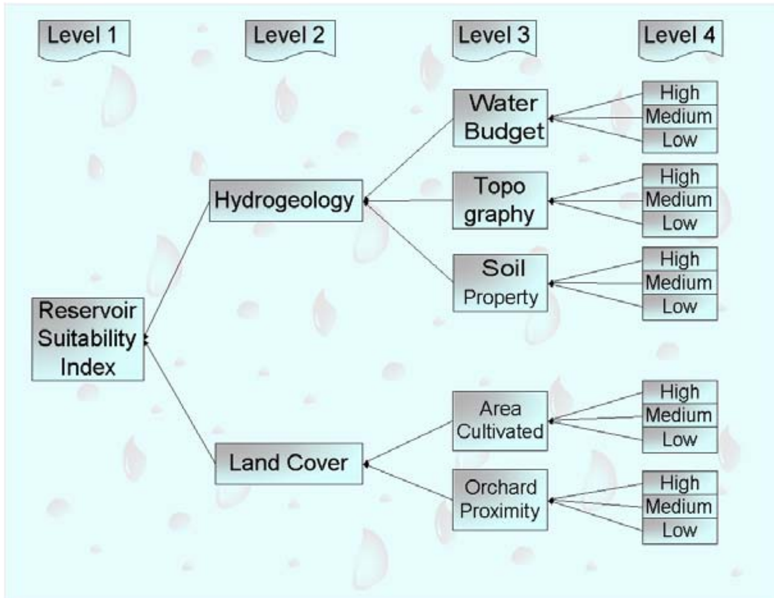

Figure 1: The scheme followed in the Hydro-Spatial Analytical Hierarchy Process.

iii) The determination of relative importance weights for sub-factors

Related selection criteria (shown at level 2 of Figure 1), subcriteria (shown at level 3 of Figure 1), and attribute classes (shown at level 4 of Figure 1) are compared to each other in pairs in order to develop relative importance weights (RIW) for all elements in the decision hierarchy structure. All pairs of attribute classes that belong to the same level are compared to each other. Experts qualitatively judge all sub-factors for their RIWs in influencing the corresponding sub-factor in the neighboring upper level of the hierarchy structure in a numerical scale. Table 1 shows the scale used to represent different preference degrees in this case study, and Table 2 shows the resulting RIWs after the pairwise comparison of the attributes of the various criteria in each level of the hierarchy structure.

Table 1: Levels of preference and their corresponding numerical expression

Preference level	Numerical expression
Equal preferences of indifference	1
Weak preference	3
Strong preference	5
Demonstrated preference	7
Absolute preference	9
Intermediate values	2, 4, 6, 8

Table 2: Relative Importance Weight stepwise calculation.

Attribute Value	Attribute Value 1	Attribute Value 2	Attribute Value 3	Eigen Value	Relative Importance Weight
	High	Medium	Low		
High	1	5	9	3,557	0,735
Medium	1/5	1	5	1,000	0,207
Low	1/9	1/5	1	0,281	0,058
	Water Budget	Topography	Soil		
Water Budget	1	8	9	4,160	0,798
Topography	1/8	1	3	0,721	0,138
Soil	1/9	1/3	1	0,333	0,064
	Area Planted	Proximity			
Area Planted	1	7		2,646	0,875
Proximity	1/7	1		0,378	0,125
	Hydrogeology	Land Cover			
Hydrogeology	1	4		2,000	0,800
Land Cover	1/4	1		0,500	0,200

iv) The calculation of the RSI for all tested locations

The RSI of a potential reservoir site is then calculated as a function of the RIWs of all the contributing criteria.

v) Ranking locations based on the calculated values of their indices

The computed RSI values are grouped into several classes, and the investigated potential 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 as shown in Table 3.

Table 3: Suitability score classes.

RSI Range	Suitability Class	Suitability Score	Suitability Score Class
0	Non Suitable	0	E
0-0.16	Weakly Suitable	1	D
0.16-0.32	Moderately Suitable	2	C
0.32-0.48	Suitable	3	B
>0.48	Highly Suitable	4	A

MODEL DEVELOPMENT

Experimental Site

The study area extends over 335 km^2 in the village of Irsal characterized with a continental climate. Elevation ranges between 1000 and 2600 m. Irsal, similarly to semi-arid areas, is characterized by low and erratic precipitation level with high yearly variation. The 10-year average annual rainfall is 296.5 mm with a range varying between a minimum of 183.6 mm and a maximum of 443.5 mm. This climate variability is one of the major constraints facing dryland agriculture (Figure 2).

Figure 2: An overview of the landscape in Irsal.

GIS Analysis

For the first step, all needed spatial coverages were assembled either from paper source or digital format (Figure 3):

a) Base and Topographic Maps were digitized from hardcopies.
b) Land Cover Map was processed using a satellite image, followed by ground truthing through field visits to random location of the study area.
c) Soil Map was clipped from the digital soil map of the country, supported by extensive fieldwork through soil sampling and lab analysis.

Both the stream network and the subwatershed map were then developed.

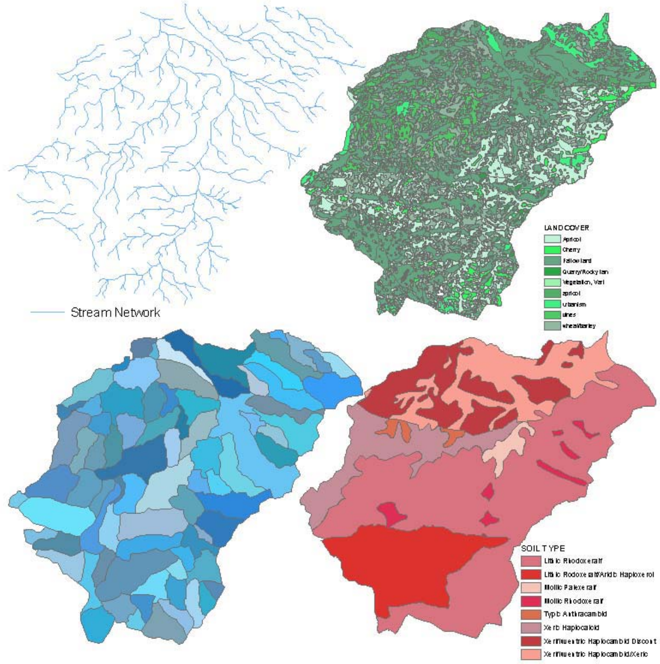

Figure 3: GIS input maps: stream network, land cover, soil type and subwatershed maps.

Hydrological Analysis

Meteorological data for Irsal and its surroundings is scarce for a multitude of reasons. Five weather stations provided ten years of data that is scanty and does not consistently include all the parameters. As most hydrologic data is estimated through surrogates, a monthly time step was adopted.

- Within WMS, the hydrologic modeling was performed at the subwatershed level.
- A composite curve number was computed for each subwatershed according the NRCS.
- The scanty meteorological data were filled and used as input to HEC-1 for generating hydrographs and synthetic runoff on a subwatershed level.

An attempt was made to simulate the water budgets of the watersheds using the two monthly conceptual lumped models, Minrun and Wbudg. Most of input variables were used through surrogates as data is lacking. Both models proved to be suitable for arid regions; however, they were not successful in simulating the water budget at the subwatershed level in this application, probably because of the known complexity of arid hydrology. Therefore, the runoff figures were used in later stages of the study not the net direct runoff produced by these two models.

Analytic Hierarchy Process (AHP) Analysis

The developed AHP was used to investigate all potential locations for water harvesting reservoirs in the study area. For each outlet the RSI was calculated that determined the suitability of the contributing subwatershed. Two scenarios, in which the preference weights for soil and slope subfactors were exchanged, were undertaken to test for the variations in suitability. Sensitivity to RIWs is important in understanding how ranks may shift given different weightings. Finally, based on the DEM and the subwatershed divisions shown in Figure 4, a common suitability score map was generated (Figure 5). A common score consisting of the sum of scores in each scenario evaluated the performance of each subwatershed. According to Figure 5, six subwatersheds are classified as class E (here to be excluded), forty six as class D, seventeen as class C, two as class B, and eleven as class A (best class). These class-A subwatersheds are the ones whose outlet are the best potential sites for water harvesting reservoirs. Further investigation needs to be centered on these.

As a practical outcome of this study, a water harvesting reservoir was actually excavated at the outlet of the highest ranking watershed.

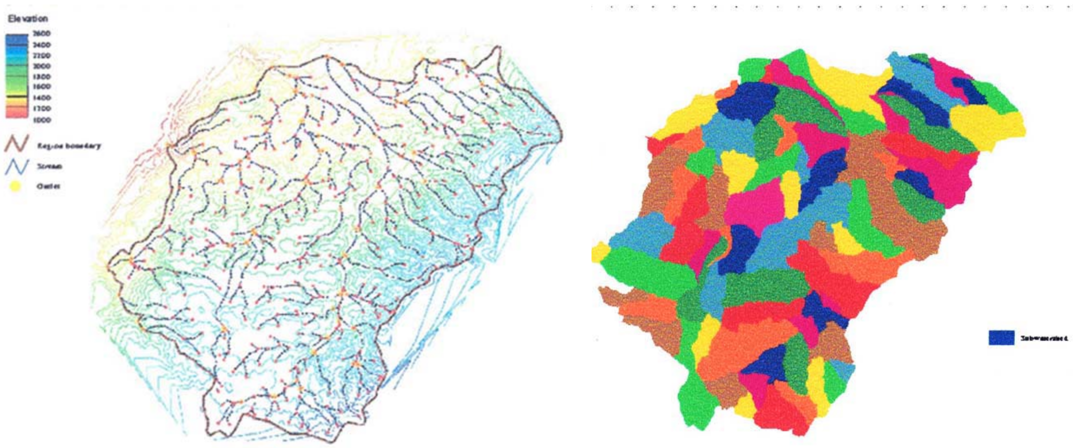

Figure 4: Output maps showing the DEM for the study area and the subwatershed divisions.

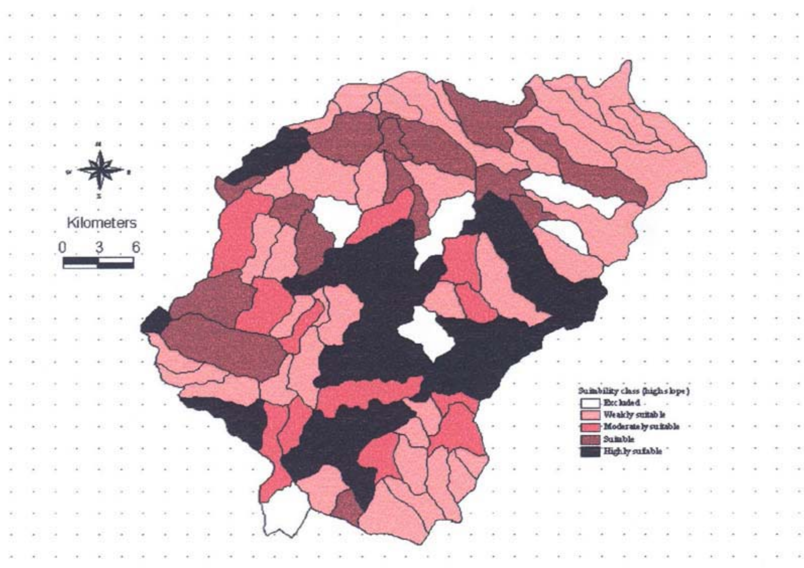

Figure 5: Suitability ranking for the subwatersheds.

CONCLUSION

The Hydro-Spatial AHP methodology for siting small water harvesting reservoirs combines the capabilities of GIS, hydrologic modeling, and AHP. The application of the methodology shows that it works efficiently for siting such reservoirs. Moreover, the methodology is highly flexible regarding the number, types, threshold values, and RIWs of decision criteria on which the reservoir siting process is based. 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 RIWs is based on subjective expert preferences. Therefore, special care should be taken in developing these RIWs that should always be defendable and subject to cross checking. Furthermore, the lack of historical data for weather and hydrology forced the use of a large time step for analysis and forced the use of approximation techniques. Nevertheless, this method still provided a valuable tool for site selection in remote areas.

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