GIS-based decision support system for identifying potential sites for rainwater harvesting

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Available online 3 August 2007

Abstract

Identification of potential sites for rainwater harvesting (RWH) is an important step towards maximizing water availability and land productivity in the semi-arid areas. However, selection of appropriate sites for different RWH technologies on a large scale presents a great challenge, since the necessary biophysical data and infrastructure are often lacking. This paper presents a geographic information system (GIS)-based decision support system (DSS) that uses remote sensing (RS), limited field survey to identify potential sites for RWH technologies. The input into the DSS include maps of rainfall, slope, soil texture, soil depth, drainage and land use/cover and the outputs are maps showing potential sites of water storage systems (ndiva), stone terraces, bench terraces and borders. The Model Builder in the Arc View GIS was used as a platform for the DSS. Two sites in the Makanya watershed, in Kilimanjaro Region, Tanzania, were used for testing and validation of the DSS. The results reflect specific suitability levels of parameters and weight of factors; for example, near streams (drainage) with slope ranges from moderately steep to steep (10°–30°) are potential sites for ndiva locations whereas moderately undulating to steep slopes (5°–10°) with unstable soils are potential sites for stone terraces. Moderately undulating slopes (5°–10°) with clay, silt clay and sandy clay soils are potential sites for bench terrace and gently undulating slopes (2°–5°) with clay, silt clay and sandy clay soils are potential sites for borders. The results from testing and validation of the developed DSS indicated that the tool can be used reliably to predict potential sites for RWH technologies in semi-arid areas. Most of predicted RWH technologies during testing were found within very highly and highly suitable locations (41.4% and 40%, respectively) also in validation 36.9% of RWH technologies were found within the moderately suitable followed by very highly suitable and highly suitable both with 23.6%. Despite the good results, it is recommended that more work be carried out to refine the model and to include other pertinent ancillary data like socio-economic factors to increase its usefulness.

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Keywords: Rainwater harvesting technologies; Remote sensing; Geographic information systems; Decision support system

1. Introduction

Rainwater harvesting (RWH) is widely practiced in Tanzania (Gowing et al., 1999). Farmers practise RWH through valley farming, which involves intensive cultivation of valley floors/bottom, where runoff from slopes is concentrated. In semi-arid central parts of Tanzania (e.g. Dodoma, Singida, Shinyaga), since the 1920s farmers have developed extensive flood irrigation techniques for paddy rice. Farmers cultivate rice on sediment rich lowlands (locally called “Mbuga”). Surface water from gullies originating from steep hilly areas, is diverted into small cultivation basins (so called “Majaluba”) (Mwakalila, 1992). Most of the rice produced in Tanzania originates from cropland where these RWH technologies are practised. It has enabled a significant increase in both cultivated area and in rice yields. Lameck (1994) reported a mean yield benefit of 3.22 ton/ha and 2.95 ton/ha for maize and sorghum, respectively, attributable to runoff harvested from different catchments. Elsewhere, indigenous systems such
as Jessour and Miskat in Tunisia, Tabia in Libya, Cisterns in northern Egypt, Hafaer in Jordan, Syria, and Sudan and many others are still in use (Prinz, 1994). Although unfavourable socio-economic conditions over the past decades have led to a decline in the use of these systems, increased water scarcity in most dry areas has necessitated the revival of such practices.

In recognition of the potential of RWH for improving water availability and land productivity in the semi-arid region, efforts are being made to promote the use of the technology in the region. For instance, RWH features prominently in the country’s Agricultural Sector Development Strategy (URT, 2001). There is therefore a need for a geographic information system (GIS)-based decision support system (DSS) for identifying areas with potential for RWH. This will provide a better guidance for targeting of RWH research and development projects in semi-arid regions.

Georgakakos et al. (2002) define a DSS as an interactive, computer graphics-based program incorporating appropriate mathematical optimisation and/or simulation models, sometimes together with more qualitative rule-based or linguistic algorithms, and designed to address the questions or issues pertaining to specific problems at specific sites. On the other hand, Adelman (1992) has defined decision support systems (DSSs) as “interactive computer programs that utilize analytical methods, such as decision analysis, optimisation algorithms, program scheduling routines, for developing models to help decision makers formulate alternatives, analyse their impacts, and interpret and select appropriate options for implementation”. A common feature of each of these definitions is that DSSs integrate various technologies and aid in option selection. Implicit in each definition is that these are options for solving relatively large, unstructured problems.

DSSs as management tools can assist strategy developers by; (i) defining the problem, (ii) generating alternative solutions, (iii) evaluating the alternatives, and (iv) indicating the best alternative for implementation. They have been successful in handling some watershed management and other related issues on an individual basis such as reservoir system management, irrigation scheduling and risk management (Raes et al., 1988). These capabilities have encouraged many water researchers to integrate GIS and DSSs. For example, Georgia Water Resources Institute developed Lake Victoria Decision Support System (LVDSS) to explore various planning and management scenarios in the Lake Victoria basin (Georgakakos et al., 2002). The LVDSS integrates conventional and remotely sensed data, GIS and various models for rainfall/runoff, agricultural planning and hydropower generation. Likewise, Stockholm Environment Institute (SEI) have developed Water Evaluation and Planning Tool (WEAP) (SEI, 2001); a GIS-based microcomputer tool for integrated water resources planning that operates on the basic principle of water balance accounting. Meijerink et al. (1993) also applied a DSS to the management of the Komering River basin in Indonesia.

This paper presents a geographic information system (GIS)-based decision support system (DSS) that uses remotely sensed data, limited field survey and GIS to identify potential sites for RWH technologies. The GIS-based DSS will facilitate planning, implementation and promotion of RWH activities, as well as monitoring and evaluation of land resources in the targeted areas.

2. Methodology

2.1. Sites for data collection, testing and validation

The Makanya watershed (Fig. 1) was used to provide data for development, testing and validation of GIS-based DSS. The two specific sites used for testing and validation were Bangalala and Mwembe villages, respectively. The villages were selected based on the intensiveness of RWH activities in the respective areas. Several RWH technologies exist in the villages. The technologies range from in situ RWH systems, such as tillage, stone terrace, bench terrace and border, to macro catchment systems involving use of diversion canals and water reservoirs, locally known as ndiva. It was also observed that, these technologies are rarely found individually in the field, but rather a combination of two or more of them. The rainfall pattern in the study area is bimodal, with mean annual rainfall of approximately 400–700 mm (Mkiramwinyi, 2006). The short rains (vuli) start in November and extend to January. The long rains (Masika) start in March and extend to May. The study area is dominated by an undulating landscape. The terrain on the upper part is composed of steep rocky hills with slopes ranging from 18°–52° and the altitude ranges between 830 m and 1042 m above mean sea level (amsl).

The study area is characterized by fairly uniform vegetation type. Croplands, bushlands, woodlands and riverine vegetation presently occupy the area. Open woodlands and bushlands dominate the hilly slopes of the study area whereas the croplands/cultivated land dominate the lowlands. Most of the land use in the study area is agricultural use in the form of mixed farming system. The most dominant farming system is agro-pastoralism that includes crop and livestock production. In the study villages, maize is either grown as a sole crop or mixed/intercropped with legume crops. The dominant crops are maize, beans, green grams, lablab bean, bananas, sugarcane and vegetables. Livestock kept include cattle, goats, sheep and chicken.

2.2. Decision support system

The DSS for identification of potential sites for RWH technologies was implemented in ArcView GIS 3.2. The conceptual framework is shown in Fig. 2. The DSS has three main components which are (1) data input and preprocessing, (2) main processing and (3) outputs of potential sites for different types of RWH technologies.
Fig. 1. Map showing Makanya catchment in Same District Northern Tanzania.

Fig. 2. Flow chart for identification of potential sites for different RWH technologies.
2.2.1. Data input and pre-processing component

This first component describes the data and pre-processing required for the decision support system. The basic data required include rainfall, soil depths, geo-spatial points (latitude, longitude and altitude), soil samples, aerial photographs, ground truthing data and topographic maps. The required data is entered into GIS and processed to create vector maps ready for main processing.

2.2.2. Main processing

Main processing is the most important component of the DSS. It has been implemented using Model Builder in ArcView GIS. The first part comprises of vector maps, referred to as themes in ArcView, of rainfall, soil depths, slope, soil texture, land cover/use and drainage. These themes become the input grid or layers into the Model Builder. The Model Builder uses the weighted overlay process (WOP) also known as the multi-criteria evaluation (MCE). The WOP creates an output grid/map by combining the values in multiple input grid themes. For each location, the cells in each input theme/layer at that location are weighted and then different layers are overlaid to create the output theme/map.

In this study, the input layers, in vector format, were rainfall, slope, soil texture, soil depth, drainage and land use/cover and the RWH technologies were ndiva, stone terraces, bench terraces and borders. The relative importance of each layer/factor with respect to other layers was different for different RWH technologies. For example for ndiva, drainage was more important than slope followed by soil texture, rainfall and land cover/use. The relative importance for each technology was based on various studies, including Mbilinyi et al. (2005) and Prinz (1996). However, with exception of ndiva, the values for relative importance weights (RIW) were similar as shown in Table 1. The RIW values were calculated using the pair-wise comparison matrix method in the context of decision-making process known as the analytical hierarchy process (Udo, 2000 and Saaty, 1980).

The second set of values required in the analysis is the suitability levels for a particular technology on a given factor. A detailed analysis of the suitability levels is given by Mkiramwinyi (2006). The values for each suitability category were scaled from 1 to 9 and are based on the criteria by Burnside et al. (2002) as cited in Diamond and Parteno (2004). The method has been found to be robust and reliable (Russell et al., 1997; Store and Kangas, 2001 as cited in Diamond and Parteno, 2004). The suitability levels for each of the factors for stone terraces are as shown in Table 2.

Additional tables on level of suitability for ndiva, bench terraces and borders are given by Mkiramwinyi (2006). Therefore, combining information in Tables 1 and 2 the suitability level (S) for cell i for stone terrace technology (s), $S_{si}$ is given as

$$S_{si} = (RIW_{RS} \times S_{RS} + (RIW_{SS} \times S_{SS}) + (RIW_{SDS} \times S_{SDS}) + (RIW_{SS} \times S_{SS}) + (RIW_{LS} \times S_{LS})$$

where RIW$_{RS}$, relative importance weight for rainfall layer for stone terrace; RIW$_{SS}$, relative importance weight for slope layer for stone terrace; RIW$_{SDS}$, relative importance weight for soil texture layer for stone terrace; RIW$_{SDS}$, relative importance weight for soil depth layer for stone terrace; RIW$_{DS}$, relative importance weight for drainage layer for stone terrace; RIW$_{LS}$, relative importance weight for land cover/use layer for stone terrace; $S_{RSi}$, suitability level of cell i for stone terrace in the rainfall layer; $S_{SSi}$, suitability level of cell i for stone terrace in the soil texture layer; $S_{SDSi}$, suitability level of cell i for stone terrace in the soil depth layer; $S_{DSi}$, suitability level of cell i for stone terrace in the drainage layer and $S_{LSi}$, suitability level of cell i for stone terrace in the land cover/use layer.

Similar equations were used for ndiva, bench terraces and borders. The higher the suitability number, $S_{y}$, of a given site (cell), the more suited it is for water harvesting technologies. The subscript y stands for the type of the RWH technology.

2.3. Data collection

Data collected for the two sites were soil texture, soil depth, topography, land use/cover, drainage pattern and
rainfall. Free soil survey procedure was adopted in soil sampling (Dent and Young, 1981) at a scale of 1:10000 and an observation intensity of one observation per 141 m², (1 per 2 ha). Soil textural classification was done using standard procedures (Hillel, 1980) and soil depth was categorized into different effective depth classes based on the criterion established by FAO (1990). In order to obtain accurate topography and derive slopes, differential GPS (DGPS) was used to record coordinates and elevations along transect lines, and GPS points (coordinates and elevations) were recorded every 100 meters (100 m grid) or less. Aerial photographs and topographic maps for extraction of land use/cover and drainage pattern, respectively, were collected from the Directorate of Survey and Mapping, Ministry of Land and Urban Development, Dar es Salaam. Data on rainfall from 1990 to 1992 were obtained from Mohamed Enterprise Sisal Estate and Suji Mission located in the Makanya watershed.

2.4. Data processing and analysis

In order to obtain elevation and slope maps, DGPS points were processed in a GIS environment to produce contour maps which were then used to construct digital elevation model (DEM) from which slope layers could be derived. The land use/cover was determined through interpretation of aerial photographs of 1983 at scale of 1: 65000 and Landsat TM image from 2003. Five different land use/cover types were identified and categorized using visual interpretation and then digitized to create land use/cover layers. They were cropland, open bushland, open bushland with scattered trees, open woodland with bushes and riverine vegetation. Drainage patterns (rivers) were digitized directly from the topographic sheet of 1988 at a scale 1: 50000 and buffer zones were extracted from the drainage patterns. The rainfall layer was also prepared using Arc-Info software. The processed layers, examples given in Fig. 3, in either vector or raster format were then combined in the DSS to create potential sites for RWH technologies.

2.5. Testing and validation of the DSS

Testing and validation of the decision support system were done using information obtained at Bangalala and Mwembe villages, respectively. Testing aimed at checking the quality performance and reliability of the system. Therefore, the data used for developing the system, suitability levels and relative importance weights, was used for testing. Validation was done to prove the validity of the system and therefore, data from a different location, Mwembe village, was used for this purpose.

3. Results and discussion

3.1. Potential sites for RWH technologies

Maps showing potential sites for different types of RWH technologies are shown in Fig. 4(a) and (b) for Bangalala
and Mwembe villages, respectively, with both maps overlaid on DEM. The sites shown in the maps are those identified by DSS with either very high or high suitability levels for ndiva, stone terraces, bench terraces and borders. Comparison of different technologies in Mwembe shows the area having more locations suitable for bench terraces and borders compared to other technologies. On the other hand, Bangalala village shows an even distribution of the different types of RWH technologies. This is attributed to difference in spatial variability in parameters important for identifying potential sites for RWH technologies including soil, topography and drainage (Fig. 3). For example, Bangalala being largely hilly and with more drainage networking compared to Mwembe, which is relatively flat or having very mild slopes and less drainage networking.

The actual acreages of potential sites for different types of RWH technologies as determined by the DSS for Bangalala and Mwembe villages are shown in Table 3. As depicted in Fig. 4 and in Table 3, areas suitable for ndiva in both villages are minimal (less than 1% of the total area). Bangalala has relatively more area suitable for stone terraces (8.9%) compared to Mwembe (1.4%), whereas both villages appear to offer the same degree of suitability for bench terraces. Also both villages do not appear to differ significantly in the size of area suitable for borders. The “possibly unspecified” areas (Table 3) are those areas not suitable for any of the RWH technologies.

The potential sites for RWH technologies identified and shown in the Fig. 4 reflect specific suitability levels of parameters and weight of factors. For example most acceptable sites for ndiva are located near riversstreams with slopes ranging from moderately undulating to steep. These results agree with field observations which indicated that most of the ndiva are located close to streams with slopes ranging from moderately steep to steep (10°–30°). Moreover the results agree with findings by Mbilinyi et al. (2005), that ndiva are constructed close to streams areas with steep slopes as water can easily enter and exit by gravity.

The majority of suitable areas for locating stone terraces are mainly with moderately undulating to steep slopes (5°–30°) with loamy sand soil. These findings also agree with field observations where most of the stone terraces were found on moderately steep slope. Likewise, according to Hudson (1981), stone terrace technologies are usually practised on sloping areas with unstable soils.

The majority of areas suitable for locating bench terraces are located on moderately undulating slopes (5°–10°) with clay, silty clay and sandy clay soils. The results agree with field observations and with findings obtained by Hudson (1981). Fine soils like clay and silt have high water storage capacity, which favours location of bench terraces. Soils with smaller particles like clay and silt have a larger surface area than those with larger particles, and a large surface area allows a soil to hold more water (Ball, 2001).

The majority of areas most suitable for locating borders are mainly found on gently undulating slopes (2°–5°) with clay, silty clay and sandy clay soils. Similar characteristic were observed on existing borders’ sites during field survey and the results are in agreement with findings by Mbilinyi et al. (2005) which indicated that areas with low to medium slopes together with high water holding capacity soils, like

<table>
<thead>
<tr>
<th>RWH Technologies</th>
<th>Bangalala</th>
<th>Mwembe</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Count Area (ha)</td>
<td>% Area</td>
</tr>
<tr>
<td>Ndiva</td>
<td>214   6.5</td>
<td>0.8</td>
</tr>
<tr>
<td>Stone terrace</td>
<td>1234  71.6</td>
<td>8.9</td>
</tr>
<tr>
<td>Bench terrace</td>
<td>1099  88.9</td>
<td>11.0</td>
</tr>
<tr>
<td>Border</td>
<td>1471 128.0</td>
<td>15.9</td>
</tr>
<tr>
<td>Unspecified</td>
<td>–     510.5</td>
<td>63.4</td>
</tr>
<tr>
<td>Total area</td>
<td>–     805.5</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Table 3

Proportion areas (ha) and percentages of potential sites for different types of RWH technologies in Bangalala and Mwembe villages as predicted by the DSS.
clay, silty clay and sandy clay are suitable for border construction. The relatively low cost of constructing borders on gently undulating slopes compared with steep slopes could be a contributing factor. Further, soils with high water storage capacity also have relatively high nutrient holding capacity (Ball, 2001).

3.2. Testing and validation of the DSS

Testing was done by comparing the locations of existing RWH technologies in Bangalala village and suitability of locations obtained using the DSS and the results are summarized in Table 4. Most of the RWH technologies were found within the very highly suitable locations (40%) and highly suitable locations (41.4%). In other words, the DSS categorization strongly agreed (81.4%) with the farmers’ indigenous knowledge. Furthermore, GIS, remotely sensed information and limited field data have shown the potential in locating suitable sites for RWH technologies.

Validation of the DSS was done by comparing the locations of existing RWH technologies in Mwembe village and suitability of locations obtained using the DSS. The results are shown in Table 5.

Most of RWH technologies (36.9%) were found within the moderately suitable followed by very highly suitable and highly suitable categories both with 23.6%. The fact that most of predicted RWH technologies were found within very highly to moderately suitable this indicates that the developed DSS tool can reliably be used to predict potential sites for RWH technologies.

4. Conclusions and recommendations

The application of the developed DSS shows that it works effectively to identify potential sites for RWH technologies. Moreover, the developed DSS is highly flexible regarding suitability levels and RIWs of decision criteria on which the potential sites for RWH technologies process are based. Thus subjective numbers in the suitability levels and weights of the criteria can be changed according to the study area characteristics.

The study has demonstrated the capabilities of using RS, GIS and field data for identifying potential sites for RWH technologies that may be used for development and management of rainwater harvesting programmes. Despite the fact that the developed DSS is a valuable tool for site selection in remote areas, socio-economic factors have to be given due consideration to increase its usefulness. It is therefore recommended that more work be carried out to refine the model and to include other pertinent ancillary data like socio-economic factors.

Acknowledgement

This study was supported by the Water Research Fund for Southern Africa (WARFSA).

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