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Soil-landscape modeling and land suitability evaluation: the case of rainwater harvesting in a dry rangeland environment

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ABSTRACT

The arid to semi-arid region is characterized by a scarcity of land and water resources, which threatens the livelihoods of the inhabitants. Rainwater harvesting is an important practice to improve water and land productivity and to cope with climate change in the drier marginal environments. The accurate determination of the location and types of rainwater harvesting interventions through a land suitability assessment is key to successful implementation. However, adequate information about land resources is needed. Unfortunately, the arid areas suffer from a scarcity of detailed soil information and preparation of this data is often costly and time consuming. This research examines the utility of modern soil-landscape modeling techniques to provide soil and topographic information that improves land suitability assessment. The suitability of the land for two types of rainwater harvesting – contour ridges and runoff strips – to grow range crops (Atriplex – *Atriplex halimus*) or field crops (barley – *Hordeum vulgare*) was examined. Two methods were compared for an area of 26 km^2 – spatial interpolation between observations (inverse distance weighted) using 108 points, and a soil-landscape prediction model that used terrain attributes derived from a digital elevation model (DEM). Soil depth was predicted to within ±40 cm for 89% of the field observations and surface stoniness was predicted to within ±20% for 82% using the soil-landscape model. The corresponding values using the spatial interpolation model were 81% and 73%. The agreement between the suitability classes derived from field observations and those derived from the soil-landscape prediction model was slightly better than those derived from the interpolation model. Moreover, the spatial distribution of the suitability classification derived from the soil-landscape prediction model shows a more realistic pattern and better identification of extreme land characteristics, such as rocky areas and deep soils. These results will help in generating reliable suitability maps that support the implementation of sustainable land use alternatives in the arid environment.

1. Introduction

Rainwater harvesting is an important practice which can substantially increase rainwater productivity in drier marginal environments. It is a viable option for improving agricultural production and enhancing environmental protection in arid areas (Oweis and Hachum, 2006). Rainwater harvesting is defined as "the process of concentrating precipitation through runoff and storing it for beneficial use" (Frasier, 1994), or it may be defined as the "collection of runoff for its productive use" (FAO, 1991). The scarcity of water resources in the arid areas forced people to realize the importance and role of rainwater harvesting in enhancing and securing additional water supplies. Currently, it is used as an important tool to address problems associated with climate change in environments.

Successful development of rainwater harvesting requires identification of those areas that are best suited for this. To select the most suitable type of rainwater harvesting technique and an appropriate location for it, knowledge of climate, hydrology, vegetation, agricultural practices, soils, topography, socio-economics, and infrastructure is required. Integrating rainwater harvesting within a sound farming system in the identified areas is crucial for the sustainable use of rainfall and other resources (Oweis and Prinz, 1994).

Land evaluation is concerned with the assessment of land performance when used for specified purposes (FAO, 1976) and can be defined as "all methods to explain or predict the potential use of land" (Van Diepen et al., 1991). Land evaluation analysis is considered as an interface between land resources surveys and land use

Abbreviations: DEM, digital elevation model; CTI, compound topographic index; IDW, inverse distance weighted; RMSE, root mean square error.

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planning and management (Davidson, 1992; De la Rosa et al., 2004). In addition to information about climate, hydrology, vegetation, agricultural practices and their socio-economic aspects, land suitability evaluation for implementing rainwater harvesting requires detailed field data, such as slope, soil depth, soil texture, and percentage surface stoniness (Oweis et al., 2001). Usually, these are not available and are costly to collect in the field.

Soil surveys are important sources of data that can be used to improve physical land suitability classifications, planning, and environmental protection (Ranst et al., 1996; Wu et al., 2001). However, conventional soil surveys are usually not useful for providing quantitative information about the spatial distribution of soil properties that are used in many environmental studies (Moore et al., 1993; Boer et al., 1996; Florinsky et al., 2002). Detailed soil maps that contain more information about soil properties and its spatial distribution are necessary for modern land evaluation, land suitability analysis, land resources management, land use planning, and other environmental modeling (Boer et al., 1996; Cheng et al., 1997; Zhu, 1997, 1999; Gobin et al., 2001; Park et al., 2001; Bishop et al., 2001; Hartsock et al., 2005; Salehi et al., 2003; Tomer and James, 2004; Quinn et al., 2005; Ziadat, 2005; Lark, 2007; Carre et al., 2007). Unfortunately, detailed soil maps usually cover very limited areas (Cooley, 2002; Romano and Palladino, 2002; Shi et al., 2004; Ziadat, 2007). Therefore, an alternative approach is needed (Carre et al., 2007).

Remote sensing and geographic information systems (GIS) provide wide coverage of digital elevation models (DEM) that are increasingly used to derive landscape attributes and in soil-landscape modeling (Salehi et al., 2003). Soil-landscape models enable the prediction of soil properties using the relationships between soils and landscape features and a limited set of field observations (Bruin and Stein, 1998; Campling et al., 2002). Because topography is a key parameter controlling the function of a natural ecosystem (Chaplot et al., 2006), DEMs are convenient for representing the continuously varying topographic surface of the earth (Thompson et al., 2001; Chaplot et al., 2006; Klingseisen et al., 2008). They are used to derive terrain attributes that are then used as predictors of soil attributes, which vary at different scales (Behrens et al., 2010). The spatial distribution of the predicted soil attributes is provided in a more detailed form than that provided by published soil maps (Thompson et al., 2001; Tomer and James, 2004; Ziadat, 2005).

Several soil properties (soil depth and the depth of A-horizon) were significantly correlated with plan curvature, compound topographic index (CTI), and upslope mean profile curvature (Gessler et al., 2000). Significant correlation was identified between terrain attributes (compound topographic index and slope gradient) and soil characteristics (smaller particle size, such as clay and silt). The larger particle fraction correlated better with the upstream flow accumulation area and stream power index (Gobin et al., 2001). Statistical models are used to investigate the correlation between terrain attributes (the explanatory variable) and soil characteristics (the response variables) at the field sampling points. Then spatial prediction is achieved by creating statistical models with sets of significant explanatory variables (Campling et al., 2002). Draguţ et al. (2009) introduced terrain segmentation as an alternative method for terrain-based environmental modeling.

Multiple linear regression models were implemented to predict soil attributes using terrain attributes within small watershed subdivisions and the minimum input from the field. The suitability map that was derived from the predicted soil attributes was significantly more accurate than the suitability map derived from traditional soil maps. This result emphasized that the use of soil attributes derived from the soil-landscape prediction model provides an alternative source of soil information in areas where soil maps are not available (Ziadat, 2007). This research proposes an alternative approach to predicting land characteristics, based on the terrain attributes that are derived from a digital elevation model. The utility of these predicted characteristics in improving the identification of suitable areas for rainwater harvesting is also investigated.

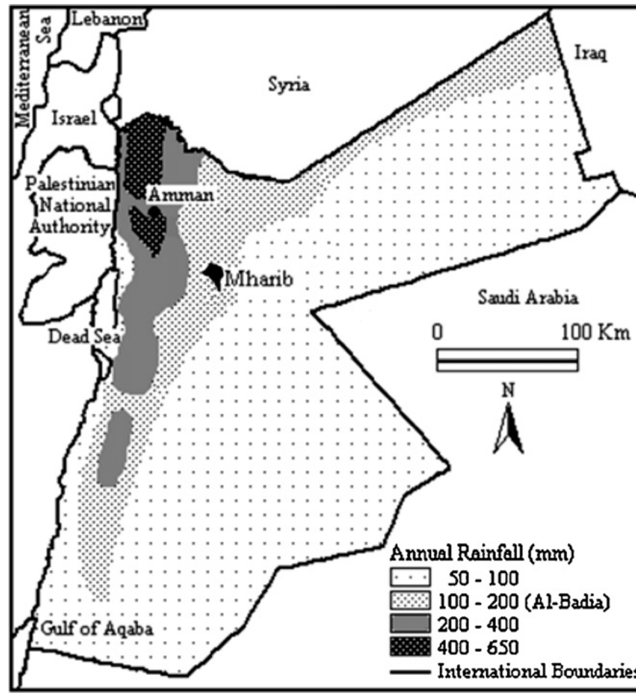

Fig. 1. The location of the study area in Jordan.
Map compiled from Royal Jordanian Geographic Center and Meteorological Department.

2. Materials and methods

The study area is located about 55 km south-east of Amman. It covers an area of 26 km^2 between latitudes 31°39′ and 31°43′ north and longitudes 36°12′ and 36°18′ east (Fig. 1). The soil of the area is dominated by Xerocherptic Haplocambids and Haplocalcids (MoA, 1995). About 75% of study area has shallow soil depth (<50 cm), highly calcareous, weakly saline, and gradients <12%. Other parts of study area have medium and deep soils ranging between 50 cm and 140 cm, with gradient between 12% and 22%. Rocks also cover 10% of the study area (MoA, 1995). Elevations ranged between 676 m and 925 m above sea level. Annual precipitation is between 100 mm and 200 mm (Ziadat et al., 2006).

Two micro-catchment rainwater harvesting interventions were chosen for this research – contour ridges and runoff strips. Contour ridges are bunds or ridges constructed along the contour lines, usually spaced between 5 m and 20 m apart. The first 1–2 m above the ridge is for cultivation, while the rest is the catchment. Contour ridges are one of the most important techniques for supporting forages and grasses on gentle to steep slopes in the dry rangeland areas. The runoff strips intervention divides the farm into strips along the contour. An upstream strip is used as a catchment, while a downstream strip supports crops. The downstream strip is usually not too wide (1–3 m), while the catchment width is determined by the amount of runoff water required. Biophysical and socio-economic requirements vary for each rainwater harvesting intervention (Oweis et al., 2001). However, for the purpose of this research, only those related to soil and topography were chosen for investigating the soil-landscape modeling approach (Table 1). The requirements for the two rainwater harvesting systems were derived from the literature and through expert consultation (FAO,