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Determining potential rainwater harvesting sites using a continuous runoff potential accounting procedure and GIS techniques in central Italy

Marco Napoli*, Stefano Cecchi, Simone Orlandini, Camillo A. Zanchi

Department of Agrifood Production and Environmental Sciences, University of Florence, Piazzale delle Cascine, 18, 50144 Florence, Italy

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ABSTRACT

The "Eight Communities of the Chianti" area, Tuscany, Italy, receives an average annual rainfall of 700–800 mm, mainly between September and December. Nevertheless, the storage capacity of the soil is not sufficient to fulfill agricultural requirements, resulting in a shortage of water from May to September almost every year. Runoff harvesting structures like farm ponds can be used to augment water supplies in agricultural areas. The suitability of a site for a farm pond requires a careful assessment of spatially varying parameters like runoff potential, slope, and land-cover. Therefore, a spatial analysis and a continuous runoff potential accounting procedure, based on the Soil Conservation Service Curve Number (SCS-CN), was used to evaluate the potential water harvesting. Model evaluation was performed based on daily runoff events recorded at 11 stations between 1996 and 2010. The statistical indices for the evaluation of the model calibration and validation were, respectively, mean percent error, −2.2% and 1.1%; mean absolute percent error, 25.2% and 23.8%; and Nash–Sutcliffe coefficient, 0.80 and 0.81. The analysis indicated that the model was able to estimate the observed runoff reasonably well. The sites suggested by the model were investigated for suitability in the field, and showed an 83% accuracy of the model. Given the increasing demand for water requirements in agriculture, this methodology could be effective in other agricultural areas with similar requirements to the "Eight Communities of the Chianti" area.

1. Introduction

In the "Eight Communities of Chianti" territory (Tuscany – central Italy), water consumption in agriculture is so high as to cause water supply problems. Several authors have shown that vineyards and olive groves, which represent 29 and 23%, respectively, of the farmland in the "Eight Communities of the Chianti" (Zanchi et al., 2010), require large volumes of water. For example, in a case study in Cyprus, Avraamides and Fatta (2008) reported an irrigation consumption of approximately 1810 l of fresh water per liter of olive oil. Moreover, the same authors reported a consumption of about 2050 l of water used in background processes, such as the production of pesticides and fertilisers. In Spain, Salmoral et al. (2011) reported that in rainfed olive groves, the agricultural stage is responsible for a water consumption of about 2.6 m^3 per kilogram of fresh product. Moreover, Garrido et al. (2010) showed a "virtual-water" consumption of approximately 1.5–2.8 and 0.15 m^3 per kg of fresh product, respectively, for olives and grape vines. In Romania, Ene et al. (2013) estimated the water consumption for grape production of 1.4 m^3 per kg of fresh product. Herath et al. (2013) assessed a water consumption in a vineyard, through evapotranspiration, as being 610 and 680 l per kg of grapes for rainfed and irrigated vineyards, respectively. Moreover, in the "Eight Communities of the Chianti" area, Zanchi et al. (2012) observed that a high water consumption was required for both vineyard and olive orchards, principally for activities related to wineries and oil mills (Table 1).

In addition, agritourism activities carried out by the farms (Nilsson, 2002; Sonnino, 2003), resulted in a yearly increase of about 11 agritourism facilities and 165 sleeping accommodations between 1996 and 2006 (CST, 2009). These activities resulted in an increase in the water requirement for the functioning of structures necessary for recreation activities, such as swimming pools and green areas, of about 0.18–0.19 m^3 $person^{-1}$ d^{-1} (Zanchi et al., 2012). Finally, the more pronounced and recurrent summer droughts, which affected Tuscany in recent years (Bartolini et al., 2006, 2008), stressed water supplies and increased demand for water during this period.

* Corresponding author. Tel.: +39 055 3288255; fax: +39 055 332472.
E-mail addresses: marco.napoli@unifi.it, napoli-marco@libero.it (M. Napoli), stefano.cecchi@unifi.it (S. Cecchi), simone.orlandini@unifi.it (S. Orlandini), camillo.zanchi@unifi.it (C.A. Zanchi).

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Therefore, "Eight Communities of the Chianti" Council proposed to identify sites to build rainwater harvesting structures, such as farm ponds, thereby permitting farms to meet their water requirements (Concepcion et al., 2006; Frot et al., 2008; Giraldez et al., 1988; Sazakli et al., 2007; Schiettecatte et al., 2005; Van Wesemael et al., 1998). The geographic information system (GIS) proved to be an effective method, in terms of cost and time saving, for the identification of potential areas for rainwater harvesting. Senay and Verdin (2004) developed the Africa water harvesting index map for conducting feasibility studies on a regional scale. El-Awar et al. (2000) used a hydro-spatial hierarchical method for identifying small water harvesting sites in dry areas. GIS was combined with multi-criteria decision making (Al-Adamat, 2008; Al-Adamat et al., 2008; Kahinda et al., 2009; Saptarshi and Raghavendra, 2009), with remote sensing derived parameters (Gupta et al., 1997; Gupta and Panigrahy, 2008; Kadam et al., 2012; Singh et al., 2009; Weerasinghe et al., 2011), and with a water balance approach (Jasrotia et al., 2009; Winnaar et al., 2007) to evaluate the rainwater harvesting potential. Sekar and Randhir (2007) developed a spatially explicit method to evaluate costs and potential benefits in water harvesting.

Among the various models, the Soil Conservation Service – Curve Number method (CN) (SCS, 1956) is one of the most versatile and the most widely used for the estimation of runoff resulting from individual rainfall events. Runoff depends primarily on the type of soil, but is also influenced by the use of the soil and the previous soil water content condition in the area (Winnaar et al., 2007). The CN method takes into account the variables listed above, incorporating them in a single Curve Number parameter (Bo et al., 2011; Mishra et al., 2008; Pachpute et al., 2009; Winnaar et al., 2007). The model can be used in a spatial domain as reported by Moglen (2000). Moreover, the method was developed further to take into account evaporation and transpiration (Hawkins, 1978; Mishra and Singh, 2004; Williams et al., 2000), and thus improving its ability to estimate the runoff at daily scale (Kannan et al., 2008).

The objective of this study was to identify potential rainwater harvesting sites in the "Eight Communities of the Chianti" area. To do so, the runoff potential of an area was estimated by using a continuous runoff potential accounting procedure in a GIS framework. Thereafter, the rainwater harvesting site map was compared with a field investigation, to measure the accuracy of the method used.

2. Materials and methods

2.1. Study area

The study area (885 km^2) was geographically defined by the border of eight Communities (Barberino Val d'Elsa, Castellina in Chianti, Castelnuovo Berardenga, Gaiole in Chianti, Greve in Chianti, Radda in Chianti, San Casciano Val di Pesa, Tavarnelle Val di Pesa) (World Geographic System 1984, 11°4′–11°33′ E, 43°17′–43°42′ N) in the Chianti territory, which lies in the center of the Tuscan region in central Italy (Fig. 1). The analysis was carried out across a broader area to avoid the inaccuracy caused by the boundary effect. The area in which the model was used is shown in Fig. 1.

2.2. Data origin and processing

2.2.1. Topography and soil

A 10 m pixel Digital Elevation Model (DEM) was used to determine elevation, slope, and aspect. The elevation ranged from 72 to 890 m, while the slope ranged from 0 to 122.8%. The soil map was constructed by a pedological characterization of the study area. A preliminary pedological map (scale 1:10,000) was derived from the official geological map of the Tuscany Region (scale 1:10,000) (Environmental Modeling and Monitoring Laboratory for Sustainable Development – LaMMA, 2012) (Fig. 2). The geological map consisted of polygons representing geological typologies having the same genesis and mineralogical composition, and therefore, characterized by pedogenic affinity. The slope gradient varied depending on the lithological nature of the substrate: steep, rugged hills were comprised of limestone or sandstone layers, whilst gentle undulating reliefs were comprised of marly and detrital substrates. The "Eight Communities of the Chianti" area was primarily subdivided into two lithological sections (Fig. 2), where sandstone dominated in the east and calcareous marl in the west, respectively. The northern area was mainly comprised of clay schist, whereas calcareous-clay soil was dominant at lower altitude. The "Chianti Macigno", consisting mainly of sandstone rock was found along the ridge of the Chianti Mountains, located in the eastern part of the area. Limestone-marl sedimentary rock was predominantly present in the central and southern regions of the area. Tuff predominated in southern area of the region (Ferroni et al., 2004).

Thereafter, the pedological map was integrated with soil data (particle size distribution, structure, organic matter, depth of the impermeable layer, etc.), determined throughout 146 field surveys in the area (Zanchi et al., 2010). Moreover, as field analysis for determining soil hydrological characteristics require expensive and time-consuming experiments, pedo-transfer functions were used. Thus, the soil analysis results were processed using the Soil Water Characteristics Hydraulic Properties Calculator (Saxton and Rawls, 2006) to derive the stabilized infiltration rate (K_{SAT}) (Fig. 3) and the retention curve. Then, the K_{SAT} polygons were reclassified according to the United States Department of Agriculture (USDA) hydrologic soil group (HSG) (USDANRCS, 2009) (Fig. 3), represented by categories A through D, for processing in the SCS-CN model. The HSG – A represents high permeability with low runoff potential; HSG – D represents very shallow or high clay content with high runoff potential; HSG – B and HSG – C are intermediate classes (Sekar and Randhir, 2007). The HSG – D is absent in the study area.

2.2.2. Land cover

The land cover elements were derived from interpretation of aerial photographs dating from 2006. It was produced by Etruria Telematica as part of the project "La carta del rischio erosivo per l'uso sostenibile del territorio agricolo del Chianti" (Zanchi et al., 2010). The land cover (10 m resolution) was classified using the Corine Land Cover map 2000 classification of the European Environment Agency (©EEA, Copenhagen, 2000).

The main land cover (up to 55%) was comprised of forest. Vineyards, olive groves, and field crops comprised 14, 12 and 12%, respectively, of the surface area, while other agricultural activities and urban areas occupied 1 and 6% of the surface area respectively. Whilst valleys were used for herbaceous crops, vineyards and olive orchards were located on moderately steep slopes.

2.2.3. Processing of meteorological data and implementation of the meteorological database

Thirty-five meteorological stations in or near the study area were selected (Fig. 4). The stations were equipped with sensors for air temperature (mod. FAR018AA, Mtx, Modena, Italy), relative humidity (FAR017AA), rain gauge (mod. FAK001BA, Mtx, Modena, Italy), wind velocity (mod. FAR202AG, Mtx, Modena, Italy) and direction (mod. FAR300BC, Mtx, Modena, Italy), and solar radiation (mod. PCTRA053, Mtx, Modena, Italy). A total of 20 stations were distributed in the study area, 7 were positioned near the "Eight Communities of Chianti" boundaries, and 8 were within a 50 km radius.

The analysis of the climate data for the 1996–2010 period showed that the area was characterized by Mediterranean climate,