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Modeling land use changes and their impact on sediment load in a Mediterranean watershed

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ABSTRACT

The aim of this study is to model potential changes in land use and evaluate their effects on sediment load in a Mediterranean watershed, the Carapelle, in Southern Italy. For this purpose, a set of Landsat Thematic Mapper (TM) images were processed to generate three different land use maps for 1987, 2002, and 2011. The images were corrected for geometric distortion and atmospheric interference before performing an unsupervised classification and decision expert system post classification. The land use maps for 1987 and 2002, derived from the Landsat TM processing, were analyzed using a Land Change Modeler (LCM) module to identify transitions from the first land cover type to the second. The transitions were modeled using a multi-layer perceptron (MLP) neural network to create transition potential maps, which provide the controls for subsequent dynamic land use change predictions. The model produced a predicted land use map for 2011 using Markov Chain analysis, which was validated with the actual 2011 land use map. Consequently, a land use scenario (S1) for 2035 and 2050 was predicted, taking into account the current constraints and management options. LCM was further used to define two additional scenarios (S2 and S3) both for 2035 and 2050 based on different land management options.

Finally, the Annual Agricultural Non-Point Source Pollution Model (AnnAGNPS) was used to estimate the effect of the predicted land use changes on sediment load after model calibration, using a five-year dataset registered at the Ordona monitoring station.

The land use change analysis revealed low transformations from 1987 to 2011. Equally, land use changes were low for the base scenario (S1) so moderate variations in sediment load were estimated. The changes in land use were more significant for the additional scenarios (S2 and S3) and consequently the model estimations underwent major variations, with a significant reduction of soil erosion. The associated utilization of land use change analysis and AnnAGNPS modeling demonstrates how land use management options can be adopted to reduce potential watershed sediment load.

1. Introduction

Land use and land cover (LULC) change is a complex process that can affect erosion and sediment load rates in a watershed (Abdelwahab et al., 2014). Climate and several human activities are capable of exacerbating LULC change (Pelacani et al., 2008; Leh et al., 2013) and the dynamics of erosive processes. Severe alterations of LULC, due to increases or decreases in human population and response of the population to economic opportunities (Lambin et al., 2001; Chung et al., 2011), have numerous consequences for terrestrial and aquatic environments (Wilson and Weng, 2011). For this reason, the understanding of recent land use changes and how these changes will occur in the future is of fundamental importance (Rounsevell et al., 2006). This knowledge is crucial for decision support procedures to identify appropriate land use policies (Romano et al., 2015), and for decision makers, environmentalists and planners in the development of plans to tackle environmental issues (Theobald and Hobbs, 2002; Maestas et al., 2003).

Many studies have been performed on the impact of land use changes on hydrology, water quality, and erosion at the watershed scale (Jeppesen et al., 2009; Tu, 2009; Feng et al., 2010; Alatorre et al., 2012; Wang et al., 2016). These studies found that the hydrological cycle and erosion processes are closely connected to land cover changes. Other studies focused on the impact of urbanization on hydrology (De Fries and Eshleman, 2004; White and Greer, 2006; Cuo, 2016), reporting that an increase of human settlements causes a decrease in infiltration and an increase in runoff. Fewer studies have addressed the combined effect of land use and climate changes on hydrology and surface water

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quality, as well as on erosion (Asselman et al., 2003; Chang, 2004; Li et al., 2009; Tu, 2009). Some of these works present responses that are simplified or not fully understood at the sub-watershed scale (Wilson and Weng, 2011). Other studies focused on the impact of land use changes on runoff and sediment connectivity at a watershed scale (López-Vicente et al., 2013; Lizaga et al., 2017; Persichillo et al., 2018).

An increasing number of studies have highlighted the importance of remote sensing multi-temporal imagery in understanding landscape dynamics (e.g., Rawat and Kumar, 2015). Remote sensing data, processed using geographic information system (GIS) software, have proven to be a very useful tool in land use studies, especially to detect, map, and model land cover patterns occurring in a given area over a determined period of time (Kahya et al., 2010; Rawat and Kumar, 2015). The integration of remote sensing with specific GIS supported hydrological models can substantially assist not only the investigation of land use changes, but also the influence of these changes on soil degradation and river system quality.

Many studies (Lopez et al., 2001; Petit et al., 2001; Rounsevell et al., 2006) have focused on predicting future land use composition, however, only a few have combined this analysis with hydrological models to predict potential water quality and soil erosion impacts (Chung et al., 2011; Praskievicz and Chang, 2011; Leh et al., 2013). For this purpose, a large number of hydrological models are available, such as the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998), ArcView Generalized Watershed Loading Functions (AVGWLF) (Evans and Lehning, 2001), Hydrological Simulation Program—Fortran (HSPF) (Bicknell et al., 1996), and Annualized Agricultural Non-Point Source Pollution (AnnAGNPS) (Bingner et al., 2012). AnnAGNPS, in particular, was developed to evaluate the impacts of agricultural non-point source pollution on water quality (Bingner et al., 2012).

In this study, we investigated the impact of LULC changes on sediment load in the Carapelle watershed (Northern Puglia, Italy) with the combined use of satellite remote sensing, GIS, and hydrological modeling. Given the extension of the Carapelle watershed (506 km^2) and the complexity of its land cover distribution, remote sensing was considered to be an essential tool for the extensive study of land cover patterns in a realistic time frame at reasonable cost. Furthermore, the integration with GIS provides a useful tool for data analysis, update, and retrieval (Chilar, 2000). The specific objectives of the study are to:

- analyze historical and actual land use maps, starting with the preprocessing of Landsat 5 TM images up until their classification and expert post classification;
- identify and validate the trend of land cover change (with the help of a change analysis module), and predict a possible future scenario of land use (base scenario, S1), for years 2035 and 2050;
- individuate two additional land use scenarios (S2 and S3), both for years 2035 and 2050, based on different management options, developed according to directives dictated by the European Planning and European Agricultural Fund for Rural Development (EAFRD);
- evaluate the impacts of these predicted land use scenarios on sediment load at the watershed and sub-watershed scale.

2. Material and methods

2.1. Study area

The study was conducted in the Carapelle watershed, located in Northern Puglia, Southern Italy, and mouthed at the monitoring station of Ordona bridge (Fig. 1). The Carapelle torrent crosses Northern Puglia and parts of the Campania region. The torrent furrows the Daunia Mountains and, after crossing the Tavoliere Floodplain, flows into the Adriatic Sea. The hydrological regime is torrential as flood events are associated with intense and short-term rainfalls (Bisantino et al., 2010). The sediment transport is characterized by fine suspended materials and occurs mainly during the flood events (Gentile et al., 2010). The climate is typical Mediterranean with warm, dry summers and mild, moist winters; the average yearly rainfalls range from 450 to 800 mm $year^{-1}$, and the average monthly temperatures range from 10 to 16 °C (Trombetta et al., 2016).

The watershed area is 506 km^2. Altitudes range between 120 and 1075 m a. s. l., while the average slope is 8.2%. The mountainous areas of the watershed are subjected to considerable erosion, as shown by the high rates of suspended sediment transport during flood events (García-Rama et al., 2016). They are constituted by flysch formations, while the alluvial plain is characterized by clay-sand Plio-Pleistocene sediments (Abdelwahab et al., 2016b). Soils in the area mainly belong to the Entisols class with a fine clay-loam texture; the organic matter content is low and the fertility is prevalently natural. The plain and low hilly areas are mainly used for wheat cultivation and, to a lesser degree, olive orchards and agricultural crops, while deciduous oaks and hardwoods (*Quercus pubescens* s.l. and *Quercus cerris* L.) cover the higher slopes together with coniferous, pasture, and meadow (Aquilino et al., 2014). The area occupied by each land use and its percentage compared to the total watershed area is reported in Table 1. A monitoring station that provides water discharge and suspended sediment transport data is located at the watershed outlet (Gentile et al., 2008).

The study area has a very low population density (49 inhabitants per km^2). Eight municipalities fall within the watershed boundary, the most populated is Ascoli Satriano, with 6204 inhabitants, while Rocchetta Sant'Antonio is the least populated, with 1843 inhabitants (source: ISTAT, 2017). The entire territory has a predominant agricultural vocation. Cereal cultivation (winter wheat) is the main agricultural resource. The trend which led to a continuous deforestation, from the first half of the nineteenth century, is actually stopped (Massafra and Salvemini, 2005). Trade is scarcely developed throughout the area; the mining activity is limited to a site close to the outlet at Ordona bridge. Even if several dams have been built on watercourses in northern Puglia (one on the Fortore, seven on the Ofanto and one on the Celone), there are no dams along the Carapelle. A decreasing trend of annual rainfall was observed in the area from 1921 to 2001. This trend is mainly due to a series of scarce annual rainfalls from about 1980, with the 1988–1992 and 2000–2001 periods as the driest (Polemio and Casarano, 2008).

2.2. Landsat images processing

The Landsat 5 TM images were chosen for their appropriate spatial resolution and for being the longest continuous record of image data observations available. The Landsat TM data and imagery provided by the later series of Landsat sensors (MSS, ETM, ETM +, OLI) have been extensively used for land cover analyses since the start of the Landsat program in 1972 (Kahya et al., 2010; Sexton et al., 2013). The TM sensor images are available in six reflective bands with a spatial resolution of 30 m and thermal band of 120 m.

The images used in this study were acquired by Landsat TM sensors on May 19, 1987, June 22, 2002, and June 22, 2011, and downloaded using the EarthExplorer Get Data tool (http://earthexplorer.usgs.gov) of the U.S. Geological Survey (USGS) Landsat web page. The images were chosen from those taken during the spring season, before the crop harvest, with complete lack of cloud cover in order to meet the observation requirements revealing both natural and human-induced land cover changes.

Each TM scene was corrected for geometric distortion using the TerrSet cubic convolution resampling type with an RMS of about 0.2 pixels. Radiance corrections for atmospheric interference were performed using the Chavez (1996) Cos(t) model. These corrections improved the comparison capacity between images taken from different acquisition dates, as in the case study, and/or by different Landsat sensors. The Cos(t) model incorporates all elements of the dark object subtraction method (Jensen, 2005) for haze removal, as well as a procedure for estimating the effects of absorption by atmospheric gases and