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Hydrological response to land use and climate changes in a rural hilly basin in Italy

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A R T I C L E I N F O

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A B S T R A C T

During the past sixty years, the social and economic development causes a change of traditional activities and a movement of the population towards urbanized areas in different regions of Italy. The replacement of vegetated land surface with impervious surface areas changed the hydrologic fluxes of a drainage basin with important consequences on the basin resilience to rainfall events. The main objective of this paper is to present the methodology and the results of a study for quantifying and analysing the hydrological responses to land use and climate changes by means of ArcSWAT model. The case study was the runoff dynamic of the Elsa river basin which was analysed by climate and land use change along more than fifty years (1954–2007). Results showed that, the model was effective in simulating daily base, peak and total runoff, scoring a very good performance. Analysis indicated that given the same climatic conditions, changes in land use played a considerable role since in peak and total runoff formation that were increased with the increase of artificial surfaces and specialised agriculture. This type of analysis proved to be effective in analysing past and future hydrological dynamics of the basin. Our findings suggest that such an approach could help policymakers involved in the land use planning in taking into account land use change, since it can amplify the effects of climate and demographic changes on basin hydrodynamics.

1. Introduction

The social and demographic changes related to economic development during the past sixty years have had contrasting impacts around the world (MacDonald et al., 2000; Stonestrom et al., 2009). The hilly countryside suffered depopulation and abandonment of traditional activities, while plain areas experienced an increase of population and industrial activities. Moreover, the socio-economic development drove land use changes such as conversion of cropland to urban area as well as changes within land use and land cover classes such as a change of crops or crop rotations (Stonestrom et al., 2009). Tuscany (central Italy) experienced an economic growth over the past sixty years, which results in the expansion of urban, industrial and commercial areas at the expense of agricultural plains. According to the “6th General Census of Agriculture” (ISTAT, 2010), Italy and Tuscany registered about 50% reduction of farms respect to 1982 and about 25% decrease of land dedicated to agriculture. Furthermore, large extension of homogeneous cultivations (specialised agriculture) was preferred to small heterogeneous cultivation patterns. Moreover, agriculture was subjected to the transition from traditional agronomic practices to agricultural mechanization that negatively affected the extension and intensity of agricultural drainage system, thus reducing the effectiveness of its function (Landi, 1989). In this context, from 1950, the reduction in ditching, tile draining and channelization activity was huge, particularly in agricultural upland areas. Since the early 50s, the new olive orchard and vineyards, which in Tuscany were mainly located on terraced hillslopes for reasons related to both tradition and quality of production, were planted up and down the slope to make machine operation more feasible and cheaper (Napoli and Orlandini, 2015; Napoli et al., 2016). The consequence of this is the lack of structures controlling runoff, such as the setting up of an adequate drainage system or implementing conservation practices can make a watershed less resilient to the intense storms. This could be amplified by the projected increase of extreme rainfall events in the Mediterranean area (Stocker et al., 2013).

Because of the importance of this societal and economic change, the Soil Thematic Strategy of the European Commission pointed out that the land surface covering by impermeable material, such as buildings and roads, is one of the major threats to soil quality and functionality (COM, 2006). In fact, urbanization determines loss of fertile soils, reductions in infiltration, canopy interception and groundwater re-

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charge of the basin (Aronica and Cannarozzo, 2000; Rose and Peters, 2001), and has the potential to increase runoff, resulting in changes in flood frequency and intensity, as well as annual and seasonal flows (Brath et al., 2006; Costa et al., 2003; Crooks and Davies, 2001; Huang et al., 2008; Olang and Furst, 2010; Poelmans et al., 2011; Wang et al., 2006). Together with changes in land cover, systematic changes in the climatic variables involved in the water cycle [e.g. precipitation, temperature and evapotranspiration (ET)] may induce notable alterations in the runoff released by hillslope.

In response, public policy decision-making processes are now seeking both economic and conservation goals. More informed decisions for basin planning and water allocation must rely on the better understanding of highland basin hydrology and the relationship between land use practices, flow generation processes, and associated water distribution and use. Furthermore, the ability to evaluate basin hydrology beyond just stream flow is crucial for determining spatially-explicit relationship between landscape structure, configuration of land use change, and the hydrology across the landscape. Within this context, managers of basin areas can be helped by tools for assessing the impact of rainfall regimes and land use changes on runoff generation, as well as for planning land policy to prevent and mitigate negative impact like soil erosion and floods.

Several studies investigated hydrological condition changes induced by land use or by climate, as well as their combined effect (Ghaffari et al., 2010; Juckem et al., 2008; Semadeni-Davies et al., 2008; Wang et al., 2008; Cuo et al., 2009; Li et al., 2009; Ma et al., 2009; Choi, 2008; Franczyk and Chang, 2009; Dams et al., 2008; Tu, 2009; Qi et al., 2009; Wijesekara et al., 2012). However, most of these studies used hydrological simulation models fed by data provided by climate change or land use future scenarios (Dams et al., 2008; Chung et al., 2011; Wijesekara et al., 2012), while only few studies investigated land use change impacts on water resources on concrete data like historical data series (Wagner et al., 2013).

Our study was focused on the Elsa river basin that was affected by heavy rains that often create flood conditions in towns and settlements along the river and these occurrences were well studied by the regional water authority (PGRA, 2016).

The objective of this study was to present a methodology to analyse the impacts of climate and land use changes on the runoff generation and demonstrate the potential application of such a methodology for the improvement of land management towards a sustainable development.

For the purpose of this study land use changes in the Elsa river basin were identified and quantified over a period of 54-year by analysing 5 orthophoto images (1954, 1978, 1988, 1996, and 2007); the ArcSWAT 2009·93·7b hydrologic model (Neitsch et al., 2011) was calibrated, validated and used to quantify impacts of land use change on runoff formation.

2. Material and methods

2.1. Study area

The Elsa river is located in Province of Florence in central Tuscany (Italy) (WGS84 – lat 43°27′–43°67′ N; lon 10°88′–11°36′ E) (Fig. 1). The study basin covers an area of about 931 km^2 with elevations varying from 46 m a.s.l. at the runoff station (near Castelfiorentino, Florence) to 300 m a.s.l. at the river head. There are 18 municipalities that are fully or partially within the basin area. Population estimates as of 2011 (ISTAT, 2011) indicated that approximately 116,570 people lived within the basin area with a density of 125 people/km^2. The climate is typical of the European Mediterranean area, with average annual values for rainfall and temperature of 847 mm and 13.7 °C over the last 50 years, respectively. The rainfall is usually concentrated mainly in two periods: September to December and March to May (Napoli et al., 2014). The Elsa river, the main stream in the basin, is about 52 km long and flows in a south–north direction with an average streamflow of about 5.4 $m^3 s^{-1}$.

The major soils in Elsa basin can be schematically summarized as follows (Fig. 2). Pliocene sand derived soils, mainly characterized by a sandy-loam texture (Calcaric Cambisols and Haplic Calcisols; FAO, 1998) were predominant in the north-western border of the basin, while Pliocene clay derived soil were predominant in the north (Vertic Cambisols and Calcaric Regosols). The Elsa river valley floor was characterized by silty loam soil originated over alluvial deposits (Calcaric Cambisols). Pliocene clay originated soil (Silti Calcaric Cambisols and Calcari Stagnic Cambisols), characterized by a texture ranging from silty loam to sandy clay loam, dominate the central part of the basin. Sandy loam soils (Calcari Epileptic Cambisols) and while clay soils (Chromi Profondic Luvisols) were predominant in the east of the basin in high steepness and moderate hillslope, respectively. Silty clay loam soils were found in the south-west (Calcaric Cambisols). While, travertine rock originated soil (Cutani Chromic Luvisols), mainly characterized by a clay texture, were found in the south.

2.2. Data for modeling

The study was conducted using meteorological and hydrological data across the period 1954–2010 provided by Regional Hydrological Service (SIR, 2016). Daily air temperature (Ta; °C) and daily rainfall depth (P; mm) were obtained from a total of twenty-five meteorological stations in or near the Elsa river basin (Fig. 1). For each station, missing data were estimated by means of linear interpolation with nearest station with known data. Then, Ta and P spatialization was carried out at daily time step by means of the regularized spline with tension (Napoli et al., 2014).

Daily runoff data were taken by the runoff station near Castelfiorentino (Fig. 1). A total of 17 years of hydrological data, having a complete daily dataset were selected. Five years (1954, 1978, 1988, 1996, and 2007) were used for model calibration and land use change analysis, while twelve years were used for model validation (Table 1).

Soil parameters such as soil profile, texture, and organic matter were derived from the 1:250,000 soil map of Tuscany (Gardin and Vinci, 2016). Stabilized infiltration rate (K_{SAT}) and retention curve were derived by soil parameters using the Soil Water Characteristics Hydraulic Properties Calculator (Saxton and Rawls, 2006). The official 10 m pixel Digital Elevation Model (DEM) of Tuscany Region (SITA, 2016) was used to derive the elevation and the slope.

The study area experienced socio-economic development during the past sixty years. In order to analyse the land use changes caused by this development, five land use classification maps (resolution of 200 m) were produced for the years 1954, 1978, 1988, 1996, and 2007 (Fig. 3). Geo-referenced aerial ortho-photos (resolution of 1 m) of the study area (SITA, 2016) were used for visual interpretation and land use type boundaries were on-screen digitized. The land use types were classified according to the Corine Land Cover (CLC) classification of the European Environment Agency (©EEA, Copenhagen, 2000). Three main land use classes were defined: artificial surfaces (comprising continuous urban fabric, discontinuous urban fabric, industrial or commercial units, road and rail networks and associated land); forest and semi natural areas (comprising broad-leaved forest and transitional woodland-shrub); agricultural land. Moreover, to represent the impact on the effectiveness of agricultural drainage system determined by the transition from traditional agronomic practices to agricultural mechanization, the agricultural land use was subdivided into four land cover classes: arable land (comprising field crops and not irrigated field crops); heterogeneous agricultural areas (comprising annual crops associated with permanent crops and complex cultivation patterns); olive groves; and vineyards.