Science of the Total Environment 538 (2015) 288–297

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Modeling suspended sediment transport and assessing the impacts of climate change in a karstic Mediterranean watershed

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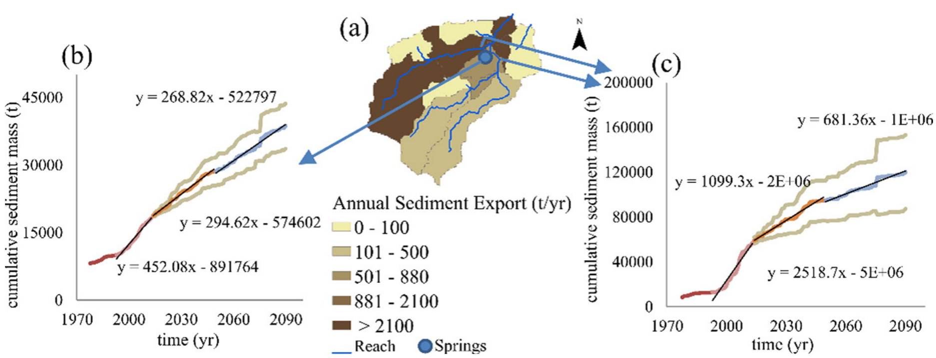
HIGHLIGHTS

- SWAT model was modified to simulate the karst contribution to the sediment transport.
- Flood events account for 63–70% of the annual sediment export on a wet or dry year.
- Major decreases in surface and spring flow during the 2010–2049 and 2050–2089 periods.
- Surface sediment export decreases significantly but has high variability.
- Climate change does not affect spring sediment.

GRAPHICAL ABSTRACT



Estimation of (a) spatial distribution of annual sediment export, (b) cumulative distribution of sediment mass originating from springs for the 1973–2090 period, (c) cumulative distribution of surface sediment mass for the 1973–2090 period, using the modified SWAT Model and three IPCC "A1B" climate change scenarios.

ARTICLE INFO

Article history:
Received 4 May 2015
Received in revised form 15 July 2015
Accepted 20 July 2015
Available online xxxx

Editor: D. Barcelo

Keywords:
Mediterranean watershed
Karstic springs
Suspended sediment modeling
SWAT model
Climate change

ABSTRACT

Mediterranean semi-arid watersheds are characterized by a climate type with long periods of drought and infrequent but high-intensity rainfalls. These factors lead to the formation of temporary flow tributaries which present flashy hydrographs with response times ranging from minutes to hours and high erosion rates with significant sediment transport. Modeling of suspended sediment concentration in such watersheds is of utmost importance due to flash flood phenomena, during which, large quantities of sediments and pollutants are carried downstream. The aim of this study is to develop a modeling framework for suspended sediment transport in a karstic watershed and assess the impact of climate change on flow, soil erosion and sediment transport in a hydrologically complex and intensively managed Mediterranean watershed. The Soil and Water Assessment Tool (SWAT) model was coupled with a karstic flow and suspended sediment model in order to simulate the hydrology and sediment yield of the karstic springs and the whole watershed. Both daily flow data (2005–2014) and monthly sediment concentration data (2011–2014) were used for model calibration. The results showed good agreement between observed and modeled values for both flow and sediment concentration. Flash flood events account for 63–70% of the annual sediment export depending on a wet or dry year. Simulation results for a set of IPCC "A1B" climate change scenarios suggested that major decreases in surface flow (69.6%) and in the flow of the springs (76.5%) take place between the 2010–2049 and 2050–2090 time periods. An assessment of the future ecological flows revealed that the frequency of minimum flow events increases over the years. The trend of surface sediment export during these periods is also decreasing (54.5%) but the difference is not statistically significant due to the variability of the sediment. On the other hand, sediment originating from the springs is not affected significantly by climate change.

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http://dx.doi.org/10.1016/j.scitotenv.2015.07.092

1. Introduction

Sediments play an important role in elemental cycling in the aquatic environment as they are responsible for transporting a significant fraction of nutrients and contaminants. Large suspended sediment fluxes in river catchments, which result from soil loss due to water erosion, constitute a major environmental issue (Louvat et al., 2008). Erosion is a natural phenomenon, however, the rate of soil loss caused by erosion is increased by poor agricultural practices (Bartram and Ballance, 1996). Protection of surface water resources requires control and minimization of soil loss. Therefore, an understanding of sediment transport processes and the development of appropriate methods for modeling sediment load are necessary in order to determine sediment budgets in watersheds (Reid and Dunne, 1996) and to make informed decisions about land use management and pollution control strategies (Hicks et al., 2000; Novotny, 1980; Parker and Osterkamp, 1995). A variety of modeling techniques have been developed to quantify and predict sediment transport (Merritt et al., 2003; de Vente et al., 2013).

Quantification of sediment fluxes is of utmost importance, especially in the Mediterranean and in arid and semi-arid regions. Temporary streams and rivers are a common form of surface runoff in these regions and present unique responses to the climatic and geomorphologic regime (Lillebø et al., 2007). The karstic areas of the Mediterranean watersheds, in particular, are characterized by a complex geomorphology and erosion processes in these areas present high variability. Intense rainstorms in combination with prolonged droughts, steep slopes and high evapotranspiration, contribute to usually high and unpredictable erosion rates (García-Ruiz et al., 2013), and temporary river hydrographs which are flashy and exhibit fast characteristic response times. Temporary streams remain dry for long periods of time, and when high intensity rainfall falls upon crusted soil, water moves horizontally in a similar way with Hortonian surface flow (when rainfall exceeds infiltration capacity) (Horton, 1933), leading to flash flood events. At the same time, drought makes sediment more easily erodible, therefore during the first flash and the following rain events, sediment and nutrient concentrations are high compared to base flow conditions. The majority of modeling techniques, including the SWAT model, have been implemented on various Mediterranean watersheds (De Girolamo et al., 2015a; Gamvroudis et al., 2015).

Karsts are also very important in water resources management in the Mediterranean region, as they regulate water discharge of the karstic springs throughout the year (Moraetis et al., 2010; Kourgialas et al., 2010). They are formed from the dissolution of limestone and dolomite formations and are comprised of a highly transmissive fractured system of sinkholes, caves and springs. They consist of a carbonate rock matrix that is usually fractured with a network of connected conduits, which have openings ranging from a few centimeters up to tens of meters (Gale, 1984). The presence of sediments within the karstic systems provides for added complexity in understanding the fluid flow and solute transport within the system (Loop and White, 2001). Distributed parameter watershed models such as SWAT (Arnold et al., 1998; Nikolaidis et al., 2013; Baffaut and Benson, 2009) and HSPF (Bicknell et al., 2001; Tzoraki and Nikolaidis, 2007) have been used in the past to simulate the hydrologic response of karstic formations (Spruill et al., 2000). To date, no attempt has been made to model sediment transport in a karstic watershed.

Climate change highly affects hydrological conditions and sediment yield. As far as global soil erosion research is concerned, there is a main concern to assess the impact of climate change on the sediment cycle (Mullan et al., 2012). Many studies provide evidence that climate change can affect streamflow (Nijssen et al., 2001; Menzel and Bürger, 2002; Zhang et al., 2007; Githui et al., 2009; Kim and Kaluarachchi, 2009; Boyer et al., 2010) soil erosion rates (Pruski and Nearing, 2002; Michael et al., 2005; O'Neal et al., 2005) and sediment flux (Jiongxin, 2003; Syvitski et al., 2005; Zhu et al., 2008; Li et al., 2011; Phan et al., 2011). However, few studies have focused on the effects of climate change on sediment transport in Mediterranean watersheds (Bangash et al., 2013; Sánchez-Canales et al., 2015; Bussi et al., 2014; Nunes et al., 2013), which have been identified as one of the most prominent "Hot-Spots" in future climate change projections (Giorgi, 2006).

This study focuses on a Mediterranean Critical Zone Observatory, the Koiliaris River Basin, which is a complex hydrologic and intensively managed watershed comprising of both karstic formations and temporary rivers. The aim of this study is to develop a modeling framework for suspended sediment transport in a karstic watershed and assess the impact of climate change on flow, soil erosion and sediment transport in a complex hydrologic and intensively managed Mediterranean watershed.

2. Case study

The Koiliaris River is situated 15 km east of the city of Chania, in Crete, Greece, within the latitude 35°27′48″N & 35°20′2″N and longitude 23°59′56″E & 24°9′23″E. The catchment area is about 130 km^2, with altitudes between 0 and 2120 m amsl (above mean sea level). The area is characterized by a limestone — karstic system in the south part, which lies beneath impermeable deposits of marls and schists in the northern part. The predominant geologic formations are carbonates, quaternary-neogenic deposits and flysch formations. Rangeland accounts for 58% of the total area while cultivated areas, forests, urban areas, and aquatic areas cover 29.4%, 8.5%, 2.8%, and 0.6% respectively. Intensive cultivation and livestock grazing led to significant deterioration of the soil quality and land fertility. Soils are thin, poorly developed, following the lithology of the area.

The geology of the Koilaris River Basin region in combination with a major fault in a northeast to southwest direction contributes to the water movement towards the Stylos springs (Fig. 1) (Moraetis et al., 2010; Nikolaidis et al., 2013), thus forming the permanent flow of the Koiliaris river. The peculiarity of the karstic system of the Koiliaris River Basin is the fact that the total recharge area of the springs extends beyond the boundaries of the basin, to the southeast of the watershed boundary, and is estimated to include at least a 50 km^2 area (Fig. 1). The complexity of the area is also enhanced by the fact that there are two karstic formations situated one on top of the other with different hydraulic characteristics and thus different transmissivities. The karstic system is characterized by fast infiltration and direct connection to the conduits below.

A temporary tributary (Keramianos) and a temporary spring (Anavreti), along with two episodic tributaries, also contribute to the Stylos spring discharge to form the Koiliaris river. The two episodic tributaries drain the east part of the watershed, while the temporary tributary (Keramianos) flows over the west part. The total outflow of the basin is estimated to be 136.29 million m^3/yr with 80% to be contributed by the karstic flow through Stylos springs, while the net contribution of watershed flow (Keramianos and Anavreti tributaries) to the river is only 20% of the total flow (Kourgialas et al., 2010). The river hydrograph at Hydrometric station H1 (Agios Georgios station) (Fig. 1) is characterized by a series of flash flood peaks. These sharp peaks are mainly attributed to Keramianos tributary during the rainy season (Kourgialas et al., 2010; Moraetis et al., 2010).

The Keramianos tributary drains a small sub-catchment that generates surface runoff due to the schist geologic formation of the area. Keramianos stream flows along a karstic gorge (Diktamos gorge) and then over an alluvial plain before joining the Koiliaris river (Fig. 1). Schist formations are quite friable and in combination with the steep slopes and the adaptation of intensive agricultural practices that are common in the area of Keramianos sub-basin, the top soil becomes extremely brittle and easily erodible. More specifically, due to the abandonment of traditional agricultural practices over the years, tractors now enter and plow the terraces, leading occasionally to their collapse, and exacerbating the erodibility of the soils. In addition, overgrazing leaves the top soil unprotected and vulnerable to surface runoff. Thus,