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Review Paper

Regional scale hydrologic modeling of a karst-dominant geomorphology: The case study of the Island of Crete

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SUMMARY

Crete Island (Greece) is a karst dominated region that faces limited water supply and increased seasonal demand, especially during summer for agricultural and touristic uses. In addition, due to the mountainous terrain, interbasin water transfer is very limited. The resulting water imbalance requires a correct quantification of available water resources in view of developing appropriate management plans to face the problem of water shortage.

The aim of this work is the development of a methodology using the SWAT model and a *karst-flow model* (KSWAT, Karst SWAT model) for the quantification of a spatially and temporally explicit hydrologic water balance of karst-dominated geomorphology in order to assess the sustainability of the actual water use. The application was conducted in the Island of Crete using both hard (long time series of streamflow and spring monitoring stations) and soft data (i.e. literature information of individual processes). The KSWAT model estimated the water balance under normal hydrological condition as follows: 6400 Mm^3/y of precipitation, of which 40% (2500 Mm^3/y) was lost through evapotranspiration, 5% was surface runoff and 55% percolated into the soil contributing to lateral flow (2%), and recharging the shallow (9%) and deep aquifer (44%). The water yield was estimated as 22% of precipitation, of which about half was the contribution from spring discharges (9% of precipitation). The application of the KSWAT model increased our knowledge about water resources availability and distribution in Crete under different hydrologic conditions. The model was able to capture the hydrology of the karst areas allowing a better management and planning of water resources under scarcity.

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1. Introduction

"Karst" identifies a specific geological landscape and morphology formed by the dissolving action of water on soluble carbonate rocks such as primarily limestone, but also marble, dolomite, and gypsum. These rocks are mechanically strong but chemically soluble with high degree of secondary porosity. As a consequence, the hydrological cycle provides the primary source of energy for karst formation because water is the solvent that dissolves carbonate rocks and then carries the ions away in solution (Williams, 2004).

The process of dissolution ('karstification') leads to the development of caves, sinkholes, springs and sinking streams that are typical features of a karst system. With progressing karstification, groundwater flow in the karst aquifer develops from a flow in an interconnected fissure network to a flow concentrated in several large pipes, interconnected cavities and cave systems (EC, 2003, 2004). The downstream end of a karst system usually is a spring where the underground conduit reaches the surface as an output point from an extensive network of groundwater conduits (Smart and Worthington, 2004).

In Europe, soluble carbonate rocks are widespread in Western, Southern and Eastern part covering 35% of whole Europe (Daly et al., 2002), so that the karst processes are significant components of the physical geography of Mediterranean basins. In particular, limestones reach great thickness in Spain, southern France, Italy, the Balkan Peninsula, Turkey and in many islands in the Mediterranean (Crete, Majorca and Sicily). As a consequence, karst aquifers and springs are an important source of water supply for Mediterranean countries and special strategies are required to manage the quantity and quality of their waters.

Bakalowicz (2015) pointed out the importance to study the karst aquifer functioning and the local geological evolution in order to manage in realistic and sustainable way the water resources. The monitoring and management of these resources are recognized in Europe as an essential issue and the European Union prompted the creation of COST Actions 620 and 621 to develop a comprehensive methodology for risk assessment and for the sustainable management of karst systems (EC, 2003, 2004). Unfortunately, most countries are lacking behind in monitoring the discharge of springs or wells and the exploitation of karst aquifers in generally is inappropriate (Bakalowicz, 2015).

In this context, large scale hydrologic models are essential tools for watershed management at regional scale. Regional scale models with an appropriate discretization of watershed can adequately account for the spatial heterogeneity improving water predictions (Wooldridge and Kalma, 2001). A variety of karst models have been developed and applied to karst watersheds (Nikolaidis et al., 2013). Recently, Hartmann et al. (2015) presented for the first time the simulations of groundwater recharge in Europe with a grid-hydrological model (VarKarst-R) pointing out the importance of a characterization of subsurface heterogeneity.

Baffaut and Benson (2009) modified the SWAT (Soil and Water Assessment Tool) model to simulate faster aquifer recharge in a Missouri karst watershed (SWAT-B&B) modifying deep groundwater recharge equations, increasing the hydraulic conductivity of sinkholes simulated as ponds and losses from streams. After that, Yachtao (2009) further modified the SWAT model in order to improve the simulation of water quality and quantity in the Opequon Creek watershed (USA). The author introduced two new parameters for simulating the hydrology and nitrate transport in a sinkhole and losses from sinking streams. More recently, Wang and Brubaker (2014) proposed a non-linear modification of groundwater algorithm in SWAT (ISWAT) improving the recession and low-flow simulation. Nikolaidis et al. (2013) developed a reservoir model approach linked with SWAT to simulate karst's behavior and the recharge of springs of Koiliaris basin in Crete adding five new parameters.

All these studies indicate that a specific parameterization of aquifer discharge, return flow, stream losses and sinkholes is required in karst watersheds. In addition, Wang et al. (2014) showed that a specific database of karst SWAT soils should be used to assess the influence of soil hydrological process in a karst region.

In this paper the SWAT model was integrated with a *karst-flow model* (Nikolaidis et al., 2013; Tzoraki and Nikolaidis, 2007). Karst-subbasins were defined in order to reproduce more accurately the water balance at regional scale.

This integrated model, KSWAT model, was applied to the Island of Crete, one of the most intensively managed Mediterranean islands, where the major water use is irrigation (84.5% of the total consumption) and the main water source is karst aquifers. The growing water demand of the region makes the rational management of water resources extremely important in view of a sustainable development. Consequently, the specific objective of this study is the development of a large scale methodology for the quantification of a spatially explicit water balance of karst-dominated geomorphologies using the SWAT model in order to assess the sustainability of water use in the Island of Crete and potentially to other areas.

2. Materials and methods

2.1. Study area

The Island of Crete occupies the southern part of Greece and is the largest island of Greece and the fifth in the Mediterranean. The Island covers an area of 8336 km^2 and is divided into prefectures, including from east to west: Lasithi (1810 km^2), Heraklion (2626 km^2), Rethymno (1487 km^2) and Chania (2342 km^2) (Fig. 1a). The maximum length of the Island is 269 km and the maximum width 60 km. Four main mountains run west to east: the White Mountains in the west (2453 m), Idis mountain (2456 m) in the center, Asterousian (1280 m) in south Heraklion and Dikti (2148 m) in the east (Baltas and Tzoraki, 2013).