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Hydrologic and geochemical modeling of a karstic Mediterranean watershed

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SUMMARY

The SWAT model was modified to simulate the hydrologic and chemical response of karstic systems and assess the impacts of land use management and climate change of an intensively managed Mediterranean watershed in Crete, Greece. A methodology was developed for the determination of the extended karst area contributing to the spring flow as well as the degree of dilution of nitrates due to permanent karst water volume. The modified SWAT model has been able to capture the temporal variability of both karst flow and surface runoff using high frequency monitoring data collected since 2004 and long term flow time series collected since 1973. The overall hydrologic budget of the karst was estimated and its evaporative losses were calculated to be 28% suggesting a very high rate of karst infiltration. Nitrate chemistry of the karst was simulated by calibrating a dilution factor allowing for the estimation of the total karstic groundwater volume to approximately 500 million m^3 of reserve water. The nitrate simulation results suggested a significant impact of livestock grazing on the karstic groundwater and on surface water quality. Finally, simulation results for a set of climate change scenarios suggested a 17% decrease in precipitation, 8% decrease in ET and 22% decrease in flow in 2030–2050 compared to 2010–2029. A tool for integrated water management of karst areas has been developed, providing policy makers an instrument for water management that could tackle the increasing water scarcity in the island.

1. Introduction

Continuous habitation in the past 12,000 yr of areas prone to water scarcity such as the Mediterranean region has been primarily due to existence of reliable spring water supply derived mostly from karstic formation natural reservoirs as well as the ability of land to regenerate itself (Nikolaidis, 2011; Stamati et al., 2011). Karsts are derived from the dissolution of limestone and dolomite formations and are comprised of a high transmissivity fractured system of sinkholes, caves and springs. Such large, below-ground natural reservoirs are very important in water resources management of the Mediterranean region because they regulate water discharge of the karstic springs throughout the year (Moraetis et al., 2010; Kourgialas et al., 2010). These water bodies will play a significant role in the overall rational management of water resources of climate change impacted transitional areas such as the Mediterranean where the precipitation is expected to decrease by at least 25% with increases in the frequency of extreme events, and the average annual temperature to increase by 2–4 °C according to the IPCC (2007) scenarios. Warmer and drier conditions are expected to intensify water shortages and cause loss in biodiversity and ecosystem services (Nikolaidis, 2011).

The importance of karstic aquifers in regional water management has been recognized by the European Union (which prompted the creation of COST Action 620 to develop a comprehensive risk based methodology for the sustainable management of karstic systems) and the US EPA (which recognized the contribution of karst areas on the hydrology of ephemeral and intermittent streams) and prompted the development of tools for sustainable management (EC, 2003; Levick et al., 2008). These water bodies will play a major role in water management as they relate to water availability for potable water and agriculture (i.e. food security issues). Agriculture is a major driver in the management of water especially in Mediterranean (Albiac et al., 2006; Wriedt et al., 2009) where 75% of the total agricultural land is irrigated and it accounts for more than 60% of the total water abstractions (e.g. Spain 64%, Greece 88%, Portugal 80%).

A variety of karst models have been developed and applied to karst formation discharge around the world. Recent attempts to model karstic discharge can be classified as follows: (a) conduit flow using Manning's equation, (b) distributed groundwater model such as MODFLOW, (c) reservoir model, (d) distributed hydrologic models coupled with conduit routing and (e) distributed parameters watershed models. Rozos and Koutsoyiannis (2006) conceptualized conduit flow using Manning's equation and developed a multi-cell model consisting of reservoirs and conduits in 3D. The model was applied to Almyros spring data (eastern Crete, Greece)

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and the simulation results were compared with simulations of MODFLOW. Similar comparison of a lumped karst model with MODFLOW was also conducted by Martinez-Santos and Andreu (2010). Fleury et al. (2007) used a three reservoir model to simulate successfully soil, slow discharge and rapid discharge of Fontaine de Vaucluse karstic aquifer in southern France. A modified version of this model was used to simulate Lez spring by incorporating active ground water management (Fleury et al., 2009). A further improvement of such model was the incorporation of non-linear hysteretic discharge functions that were applied to Vensim model by Tritz et al. (2011). Zhang et al. (2011) modified a Distributed Hydrologic-Soil-Vegetation Model (DHSVM) to include flow routing in karst conduits and model the hydrologic response of a small karst basin in southwest China. Other distributed approaches to modeling karst hydrology were presented by Smaoui et al. (2012) that used the HySuf-FEM (Hydrodynamic of Subsurface Flow by Finite Element Method) code to model the Berrechid karst aquifer in Morocco as well as Kourtulus and Razack (2010) that used artificial neural network and adaptive neuro-fuzzy interface system to model the daily discharge of the La Rochefoucauld karst aquifer in south-western France.

Distributed parameter watershed models such as SWAT (Soil and Water Assessment Tool, Arnold et al., 1998) and HSPF (Hydrologic Simulation Program-FORTRAN, Bicknell et al., 2001) have been used in the past to simulate the hydrologic response of karstic formations (Spruill et al., 2000). Afinowicz et al. (2005) modified the aquifer discharge parameterization of the SWAT model in order to better simulate the quick flow response of the karst in Texas and Baffaut and Benson (2009) extended this parameterization by including sinkholes, losing streams and return flow to model flow, fecal coliforms and phosphorus in a Missouri karstic watershed. Tzoraki and Nikolaidis (2007) developed a two linear reservoir model to simulate the karst and combined it with HSPF to simulate the hydrology, sediment transport and nutrient loads of Krathis River basin in northern Peloponnese, Greece. Kourgialas et al. (2010) added a distributed snow model to the karstic two reservoir model and combined it with HSPF in order to simulate the hydrologic response of the Koiliaris River basin in Crete, Greece.

The peculiarity of karst systems such as those found in the Mediterranean relies on the fact that a spring could receive contributions from the karst that it is extended outside the watershed boundaries to which the spring belongs as well as karsts situated one on top of the other with different hydraulic characteristics and thus different transmissivities (EC, 2004). Identification of the extended karst area that contributes to the flow of the spring is extremely important in order to obtain accurate hydrologic and geochemical balances of the system (Tzoraki and Nikolaidis, 2007; Moraetis et al., 2010; Kourgialas et al., 2010). A second peculiarity in artesian karstic systems has been discussed in detailed by Moraetis et al. (2010) and deals with the diurnal variation of karst level. Barometric and temperature changes at the entrance of the sinkhole create changes to the barometric pressure above the water table of the karst, making it to operate as a bladder pump and introducing energy into the system which is transformed into a highly dispersive system causing mixing and dilution of the pollutants. Modeling of the geochemistry of the karst requires the determination of the degree of dilution (i.e. volume of water within the karst below the level of spring discharge) in addition to spring discharge.

The objective of this research was to study the hydrologic and chemical response of a karst system in an intensively managed Mediterranean watershed in Crete, Greece and then assess the impacts of land use management and climate change on the hydrologic and chemical regime of the watershed. The SWAT model was modified to model the hydrologic and chemical response of karst providing in this way policy makers a tool for integrated water management that would tackle the increasing water scarcity in the island. We have selected to model the nitrogen cycle as an indicator of both livestock and cultivation impacts on surface and ground water quality (Glibert et al. (2006). Proper management of the nitrogen cycle in intensively managed areas has become an urgent priority since it appears that nitrogen is one of the planetary boundaries for safe operating space for humanity that has been exceeded (Rockstrom et al., 2009).

2. Watershed description and available data

Koiliaris River watershed is located in the north-western part of Crete near Chania, Greece and has a watershed area of 132 km^2 (Fig. 1). Based on the geomorphologic characteristics of the basin, hydrologic modeling and the orientation of the fault system, the extended karst area that contributes to the spring flow in the watershed was located south east of the area and was estimated to include at least 50 km^2 (Moraetis et al., 2010). The watershed has an intense geomorphology with elevations ranging from 0 to 2120 m AMSL and slopes ranging from 43% (at high elevations) to 1–2% (valley). The predominant geologic formations are: limestones, dolomites, marbles, and re-crystallized limestones with cherts of the Plattenkalk, Tripolis, and Trypali series (71.8%), calcaric marls and marls – Neogene deposits (15.6%), schists (6.1%) and quaternary alluvial deposits (6.4%).

The karstic system of the White Mountains is comprised of an autochthonous geotectonic unit, Plattenkalk (Metamorphic Crystalline Limestones – Mesozoic period) and two allochthonous units, the Trypali limestones (Triassic to Cretaceous period) and the metamorphic schists (Fig. 1). The Plattenkalk nappe consists of layers of dolomites, limestones and marbles and limestone and cherts with intense bedding (in the lower boundary of metamorthosis). The Trypali nappe is highly karstified and has overthrusted the Plattenkalk nappe. The metamorphic schists overstrusted both the Plattenkalk and Trypali units mainly in the western part of the White Mountains. Neogene sediments (marls and marly limestones) have been deposited at the lower elevations of the basin over the autochthonous formation. Finally, alluvial sediments are found near the river corridor mostly in lower elevations. Fig. 1 presents the geology of the area of Koiliaris River watershed and Fig. 2 presents two geologic cross sections depicting the stacking of the nappes and the existing faults.

The stratigraphy of Crete has been formed by one dipping north and one south that meet at the north–south divide (approximately at 2000 m elevation) as well as east–west trending zones (Papanikolaou and Vassilakis, 2010). The Plattenkalk autochthonous formation in the watershed has significant east–west normal faults dipping north. At the eastern part of the White Mountains there is increased exhumation of the autochthonous nappes, while in the western part, there is stacking of allochthonous nappes that overthrust the north-west dipping of Plattenkalk. Along the Plattenkalk dipping a series of normal faults influence the creation of neogene sedimentary basins (Fassoulas, 1999).

The karst system is characterized by very fast infiltration and direct connection to the conduits below. There is a significant number of sinkholes with long downward shafts, caves and a deep conduit system (Gourgouthakas cave −1205 m, Liontari cave −1100 m; Moraetis et al., 2010). The karst system discharges in a series of permanent springs, Stylos springs at elevation + 17 m AMSL and an intermittent spring, Anavreti at elevation + 24 m AMSL. Both springs then feed Koiliaris River. The springs have an average discharge of 154 million m^3/yr (2007–2010) with very intense fluctuation between winter and summer flows. The total recharge area of the springs extend beyond the boundaries of Koiliaris River Basin to the south-east of the watershed boundary