Evaluation of the uncertainty of the impact of climate change on flow, sediment and nitrate predictions at the Koiliaris Critical Zone Observatory

Sofia D. Nerantzaki ^{a*}, Nikolaos P. Nikolaidis ^a and Dionissios T. Hristopulos ^b

^a School of Environmental Engineering, Technical University of Crete, University Campus, 73100 Chania, Greece ^b School of Mineral Resources Engineering, Technical University of Crete, University Campus, 73100 Chania, Greece

*corresponding author, email: <u>sofia_ner@hotmail.com, +306973475458</u>

Abstract

This study aims to assess the internal variability in flow and water quality predictions at a Mediterranean karstic watershed for the first time. To achieve this, we use a modified version of the deterministic Soil Water Assessment Tool (SWAT) which incorporates a model to account for the flow originating from the karstic springs (Karst-SWAT). Three emission scenarios (Representative Concentration Pathways RCP2.6, RCP4.5, RCP8.5) of the CSC-REMO Regional Climate Model (of the MPI-ESM-LR-r1 driving Global Climate Model of the EURO-CORDEX climate model ensemble) are used. The input rainfall time series are stochastically modeled using the Long Ashton Research Station Weather Generator (LARS-WG). Monte Carlo simulations for the 2019-2098 time period are used as input to the Karst-SWAT model to assess the uncertainty of the model flow, as well as nitrate and sediment transport. Results suggest that the inherent uncertainty (expressed as 5–95 percentile range divided by the mean) in the rainfall emission scenarios (15%), is propagated through the SWAT model, leading to higher uncertainty for the flow estimates (22.3%), the exported nitrate mass (17%), and the exported sediment mass (38.3%). The incorporation of internal variability assessment of emission scenarios for the estimation of the response of karstic basins to climate change is of utmost importance, since it overwhelms climate change signals in flow and exported nitrate mass until 2060. Although the internal variability of sediment export is significantly high, climate change models always indicate a stable or increasing trend compared to the reference period.

Key words: *climate change; uncertainty; internal variability; sediments; nitrates; karstic Mediterranean watershed;*

1. Introduction

Climate change impacts on water supply have received a lot of attention but relatively little is known about the respective changes in water quality, especially in the Mediterranean region, regarding sediment transport and erosion [1-6] or nitrate concentrations [7,8]. Even fewer studies have dealt with the ways that climate change affects water quality of karstic aquifers [9]. Both the quality and availability of water resources in the Mediterranean region are expected to change significantly according to the Intergovernmental Panel on Climate Change (IPCC) Synthesis Report [10]. Due to the projected changes in air temperature and rainfall, river flows are expected to be affected and the mobility and dilution of contaminants will also be influenced, but the relationships are not straightforward to capture.

Recent research has also revealed that the water management community has neglected and in many cases underestimated the uncertainties in climate change scenarios, in particular, uncertainties associated with internal climate system variability and hydrologic modelling. The inherent uncertainty that exists in the input time series can significantly affect model outputs and our confidence in the results. In this context, very few studies have addressed the internal variability problem over the Mediterranean region, where observational data foreshadow a substantial change towards higher temperatures and lower precipitation rates, and lower flows accordingly, and much less over regions with karstic formations.

The Koiliaris Critical Zone Observatory, which represents severely degraded soils due to heavy agricultural impacts such as grazing, over many centuries, represents Mediterranean soils under imminent threat of desertification due to climate change. It is located in the island of Crete, and is characterized by an uneven spatial and temporal rainfall distribution, which in combination with the intensive agricultural activity and the expansion of tourism, have made it a drought-prone region. The river basin has a composite flow system: karstic springs which supply permanent flows throughout the year and surface intermittent runoff. Karstic areas and their 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). The majority of the sediment amount in the river during flash floods originates from a highly degraded watershed drained by an intermittent tributary. Nitrate concentrations observed suggest a significant impact of livestock grazing on the karstic groundwater and on surface water quality.

The aim of this study is to assess the predictions and stochastic uncertainty of climate change in the flow, nitrate and suspended sediment predictions at the Koiliaris Critical Zone Observatory. We achieve this by using a modified version of the deterministic Soil Water Assessment Tool (SWAT) which incorporates a karstic model (Karst-SWAT), in combination with a stochastic rainfall generator (Long Ashton Research Station Weather Generator or LARS-WG), which is run under both current and future climate conditions, to generate rainfall time series with the same statistical characteristics as the original (observed and forecasted). The generated time series are used as input in the karst-SWAT model, for the simulation of flow, nitrate and sediment concentration at the Koiliaris River Basin, in order to explore the inherent uncertainty in present and future predictions.

2. Materials and methods

2.1 Case study and Data

The Koiliaris River basin is a Critical Zone Observatory that represents severely degraded soils due to heavy agricultural impact such as grazing, over many centuries. It is situated in Crete, Greece, 15 km east of the city of Chania. The catchment area is about 130 km². The karstic formations in the basin, which correspond to the Plattenkalk limestones of Fig. 1, in combination with a fault that extends from the northeast to the southwest, direct water from an extended karstic watershed area towards Stylos springs (Fig.1) [11,12], thus supplying the permanent flow of the Koiliaris river. The overall recharge area of the springs, extends outside the watershed boundaries (Nikolaidis et al., 2013) to the southeast of the watershed boundary, over an area of about 80 km² (Fig.1).

In addition to the permanent Stylos spring discharge, there is also a temporary tributary called Keramianos, a temporary spring called Anavreti, and two episodic tributaries (upstream of Anavreti, Fig.1), which combine together to compose the Koiliaris river flow system. The total flow at the basin exit is estimated at about 180 hm³/year, 80% of which is contributed by the karstic flow originating at Stylos springs, while the contribution of the surface runoff (mainly Keramianos and Anavreti tributaries) to the total river flow is 20% [3]. 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, Keramianos is the main tributary responsible for the bulk of the sediment transport in Koiliaris River. On the other hand, waters derived from the karstic springs, have a relatively constant – low – concentration [3].



Fig.1 Map of Koiliaris River Basin (Crete, Greece) showing precipitation and temperature measurement stations and the modeled extended karstic area

The agricultural land consists of olive groves, citrus groves, vines and vegetables (32.1%) grown with conventional practices such as tilling, irrigation and use of fertilizers. Intensively grazed scrubland/pasture by livestock covers large areas (67.3%) of the watershed at high altitudes and forest (0.6%). The number of animals grazing in the watershed and its extended karst is about 123,987 sheep and goats in 2001. With a grazing area of 16,875 ha, the grazing intensity is 6.8 animals/ha. According to the country's statistics, fertilizer consumption was 405,000 ton/year in 2002. Intensive cultivation and livestock grazing have deteriorated significantly soil quality and land fertility. Soils are thin, poorly developed, following the lithology of the area [12].

The data used as input to the SWAT model are provided by five meteorological stations, two of which are located within the watershed boundaries. These stations (at Samonas and Psichro Pigadi, see Fig. 1) are managed by the "Laboratory of Hydrochemical Engineering and Remediation of Soil" of the Technical University of Crete and record data every 5 minutes. The remaining three precipitation stations at Askifou, Kalives and Mouri are managed by the Region of Crete and are located outside the basin. Data from a telemetric station located near the exit of the basin towards the sea and two hydrometric stations along the Keramianos river bed, recording water level data every 10 minutes, are used to calibrate the SWAT model. In addition to the telemetric data, monthly field campaigns are conducted for both surface and ground water quality measurements (nitrate concentration among others, 2004-2010 interrupted time-series). Further details on the monitoring network and data analysis can be found in Moraetis et al. [11].

Grab samples for the determination of suspended sediment concentration were collected from the Koiliaris River at the hydrometric station H1 (Agios Georgios), on a monthly basis from 2011 to 2014. In addition, samples were also collected after every intense precipitation event in-between December 2013 and February 2014 at the station H3 which is located upstream of the gorge and corresponds to the Keramianos sub-basin.

Data from the meteorological stations are available for the 1974-2018 period (45 years). However, there are periods of missing data for all 5 stations, which are infilled using the normal ratio methodology (as suggested by [13]) and utilizing monthly correlations between these stations or stations outside the watershed. According to the method, the estimate of the unknown rainfall value is given by: $P_X = \frac{N_X}{N_A}P_A$, where P_X and P_A are the daily rainfall values of the missing data station and the station with the available rainfall data respectively, and N_X and N_A are the normal annual rainfall of the missing data station and the station with the available daily data.

2.2 Overview of the methodology

The aim of the methodology presented in this study is to assess the impact of internal variability (or stochastic uncertainty) of rainfall input on the flow, nitrate and sediment quantities transferred by the river to the basin exit of a karstic Mediterranean watershed. The input time series consist of the rainfall time series at Mouri station for the reference period (1974-2018) as well as the projected time series for the same station, based on three Representative Concentration Pathways (RCPs), i.e. RCP2.6, RCP4.5, and RCP8.5 of the CSC-REMO [14] Regional Climate Model(section 2.5). The input time series from the RCPs are imported in the LARS-WG, and an ensemble of thirty time series is generated for every initial time series. The generated time series are then used as input in the Karst-SWAT model. The model outcomes are surface runoff (provided by the classic SWAT model), spring flow (provided by the Karst-SWAT) model, nitrate concentration and sediment concentration at the basin exit (combination of classic SWAT and Karst-SWAT). The total flow of the basin is considered as the sum of the spring and karst flows. The sediment and nitrate mass are estimated by multiplying the daily concentration values at the basin exit with the corresponding flow values. The methodology is schematically illustrated in Fig.2 and the stochastic rainfall generator (LARS-WG) and the Karst-SWAT model are described in the sub-sections 2.3 and 2.4.



Fig.2 Schematic representation of the methodology followed to assess internal variability for the reference period and the uncertainty of Koiliaris river flow (total flow, sediment and nitrate export) due to climate change projections.

2.3 Rainfall Simulation

The LARS weather generator (LARS-WG) is a single-site stochastic weather generator which simulates rainfall under present and future climate conditions [15-17]. LARS-WG is chosen in order to overcome the limitations of the Markov chain model of precipitation occurrence [18-20]. The latter considers two precipitation states, wet (non-zero rainfall) and dry (zero rainfall), and transitions based only on the conditions of the preceding day. This is not always sufficient to correctly simulate the maximum dry spell length which is crucial for realistic assessment of water resources in semi-arid regions. LARS-WG has performed well compared to other weather generators by means of reproducing the statistical characteristics of observed rainfall [21]. The rainfall simulation technique followed by the latest version of the LARS-WG is described in detail in [15]. The LARS-WG utilizes semi-empirical distributions for the lengths of wet and dry day time series and for the intensity of daily precipitation. Precipitation occurrence WG is modelled as a sequence of alternating wet and dry series. The length of each series is chosen randomly from the wet/dry semi-empirical distribution for the month in which the series begins. The precipitation intensity for wet days is generated from the semi-empirical distribution of rainfall intensity on wet days for the particular month. The intensity value generated for each wet day is independent of the length of the wet series or the amount of precipitation on previous days.

LARS-WG is applied for the time-series of the Mouri station, which has the shortest period (one year) of missing data. Although located just outside the karstic watershed, Mouri is representative for the permanent springs flow and is the single station which is well correlated with the remaining 4 stations (Psichro, Samonas, Kalives and Askifou). Since LARS-WG cannot produce correlated time series at multiple locations, the remaining stations are "simulated" based on Mouri using the normal ratio methodology described in section 2.1. Thus, correlated time series are generated for the remaining four stations. The calibrated SWAT model was run using the Mouri-based rainfall time series. The results show that the fit between the predicted and observed flow values is satisfactory (see Fig.3 and section 2.4), which supports the selection of Mouri station as model input.

The effect of temperature input uncertainty on flow is also tested in the same manner as in [22]. Temperature data were available from two stations, Psichro Pigadi and Samonas, with data of daily minimum and maximum temperature available for the 1974-2018 period. The Box-Jenkins methodology [23] is used to simulate the time series of minimum and maximum temperature at both stations (Supplementary Material, Figures S1, S2). Thirty temperature realizations were simulated for each climate scenario while the precipitation input of the original time series was kept constant for each simulation. Results suggest the variability of flow, nitrate and sediment exported masses resulting from temperature uncertainty is less than 5%. Hence, the studied variables are not sensitive to temperature variations.

Therefore, for the purpose of assessing the effect of input uncertainties on the hydrological and water quality outcome, precipitation is considered as the meteorological key factor and temperature is not further considered.

2.4 The Karst-SWAT model

The SWAT model (Soil and Water Assessment Tool) is a well-known and widely used deterministic, watershed to river basin-scale, hydrological model, which operates on a daily time step. SWAT can assess the quality and quantity of surface and ground water and predict the environmental impacts of land use, land management practices, and climate change [24, 25]. In the model, the watershed is divided into smaller sub-basins in order to separate the tributaries; these are further divided into hydrologic response units (HRUs) which constitute unique combinations of soil type, land use and slope value within the watershed.

For the purpose of simulating the karstic springs flow, we use the methodology developed in [11] to define the spatial extent of the karst area, based on fault analysis and other available data and observations, and its volume by means of mass balance modeling. The SWAT model uses the precipitation as input and simulates the surface hydrologic processes (snow accumulation and melt, surface runoff, infiltration to shallow groundwater and evapotranspiration) over the karst area. The surface water is then directed to the subsurface. Deep groundwater flow in the karstic area, which feeds the spring flow, is aggregated on a daily step and provides the input to a two-part reservoir karst model [12]. The karst model parameters are calibrated, and the resulting flow time series is used as point source input at the spring location. The mass balance equations for the two-part reservoir model are solved analytically for a daily input time step [12, 26]. In this setup, a nitrate-N mass balance was included assuming that nitrate is conservative in the karst [12]. Given that the volume of the two reservoirs reflect the daily volume corresponding to the discharging water from the spring and does not account for the permanent volume of the karst below the spring level, a deep karst factor was introduced in the model equation of the lower reservoir to account for the extra dilution of the incoming chemical loads and in this way provide an estimate of the total volume of the karst (equal to 4.5). As far as the sediment transport is concerned, sediment yield from surface erosion is estimated for each HRU with the Modified Universal Soil Loss Equation (MUSLE). Thus, sediment yield is determined by the surface runoff volume, the peak runoff rate, the soil erodibility, the type of land use management and the support practices that are being followed, the slope and the coarse fragment of the soil (Williams, 1975). Sediment routing in the channel consists of two processes operating simultaneously, deposition and degradation. The aforementioned two processes are computed with a simplified version of Bagnold stream power equation. The sediment mass balance of the karst is calculated in a similar manner as the nitrate — N mass balance presented by [12] (see also Supplementary Material Equations). Manual calibration (trial-and-error method) was conducted by adjusting the erosion and sediment routing parameters that could not be obtained directly from available data. The sampling station H1 is located just downstream of the cross-section where the Keramianos tributary merges with the main river, the latter being fed by the karstic springs. Thus, the sediment and nitrate concentration at the sampling point is assumed to be equal to

$$C_{model} = \frac{Q_{karst} + Q_{surf} + Q_{surf} + Q_{surf}}{Q_{karst} + Q_{surf}} \quad (1)$$

where Q_{karst} and C_{karst} is the flow and concentration (nitrate or suspended sediment) from the karstic springs, Q_{surf} is the surface flow from tributaries (mainly Keramianos) and C_{surf} is the concentration of the surface flow. The determination of Q_{karst} is possible through the Karst-SWAT model. Eqs. (S10), (S11) (Supplementary Material) were used for the determination of C_{karst} , while Q_{surf} and C_{surf} are provided from the calibrated SWAT model. The sediment or nitrate concentration from the modified SWAT model given by Eq. (1) is expected to match the corresponding observed values at station H1.

The karst-SWAT model for the Koiliaris river basin has been calibrated using the 5 precipitation and 2 temperature stations. Details on the karst-SWAT model and the calibration for Koiliaris River Basin along with the exact equations used, can be found in Nikolaidis et al. [12] (flow and nitrates simulation) and Nerantzaki et al. [3] (sediment simulation). The methodology used for model calibration follows a three-step approach. First the hydrologic parameters of the sub-basins contributing to Keramianos tributary surface runoff are calibrated. Then, the transmission losses through the gorge are adjusted; finally, the Stylos spring flow is calibrated by first calibrating the SWAT hydrologic processes and then the karst model parameters of the extended karst. The agreement between the calibrated model for the reference period 2004-2013 (using the original rainfall time series at Mouri, and rainfall at the other four stations based on Mouri, see section 2.3) and the observed daily flow at the basin's exit is shown in Fig.3. The statistical indices suggested by Moriasi et al. [27], namely the Nash-Sutcliffe Efficiency (NSE) which is the residual variance ("noise") compared to the measured data variance ("information"), the Percent Bias (PBias) which is the deviation of data being evaluated expressed as a percentage, and the standard deviation ratio (RSR), which is equal to the root mean square error (RMSE) divided by the standard deviation of the observations, were calculated leading to: NSE=0.62, PBias=0.91 and RSR=0.62 for the daily values, and NSE=0.70, PBias=0.91 and RSR=0.55 for the monthly values. A simulation is considered adequate if NSE > 0.5, |PBias|< 0.25 and RSR < 0.7. The NSE and the RSR indices are the same as the initial model calibration (using the true values of all 5 stations) for the daily values and slightly worse for monthly values. The PBias index, though, is significantly improved compared to the initial calibration for both daily and monthly values (PBIAS equal to -22.3%).



Fig.3 Validation of karst-SWAT model output (daily flow) using rainfall input from Mouri and four other stations, with the observed daily flow at the basin's exit.

The model output for nitrate and sediment concentration at the basin exit is presented in Fig.4 (again, the graphs are a result of the model which uses the original rainfall time series at Mouri, and rainfall at the other four stations based on Mouri). A simulation is considered adequate for water quality simulations if NSE > 0.5, |PBias|< 70% and RSR < 0.7. The nitrate simulation yielded NSE equal to 0.6, PBias 45.8 % and RSR 0.65. As far as the simulation of sediments is concerned, for the 2011–2014 period, the NSE is 0.97, the PBias is 53.0 % and RSR is 0.16 for the daily records. The indices are improved compared to the original calibration [3]. The mean daily concentration is estimated at 0.81 mg/L for nitrates and 28.9 mg/L for suspended sediments.



Fig.4 Validation of karst-SWAT model output [(a) nitrate concentrations (b) sediment concentrations], using rainfall input from Mouri and four other stations, with observed data at the basin's exit.

2.5 Climate Change Scenarios

A sub-set of simulations is selected from the recent high resolution (12.5 km) climate model ensemble, the EURO-CORDEX (EUR-11) [28]. The Global Climate Models (GCMs) simulations of the EURO-CORDEX have been conducted within the Coupled Model Intercomparison Project Phase 5 (CMIP5) representing various scenarios of greenhouse gas emission pathways. The regional simulations downscale the global climate projections of CMIP5 [29] and the RCPs [30, 31]. EURO-CORDEX scenario simulations use the RCPs defined for the Fifth Assessment Report of the IPCC [30]. Among the driving realization of the ensemble's GCMs, the MPI-ESM-LR (GCM member r1i1p1) is selected, with the Regional Climate Model CSC-REMO. The selection of REMO is based on the performance of the model, which, for temperature, is best in the European, Mediterranean and North American domain, and precipitation shows highest skill scores for the Mediterranean, African and West Asian regions [14]. The latter is run for a range of Representative Concentration Pathways (RCPs), i.e. RCP2.6, RCP4.5, and RCP8.5 [30, 32].

The RCM simulated temperature and precipitation data (for each emission pathway) are adjusted for biases against a thirty-year period between 1980 and 2009 that served as reference for the correction. The quantile mapping methodology known as multi-segment statistical bias correction (MSBC) is used [33]. The bias correction of the RCM data is performed using point observations, hence the correction procedure also serves for the parameter downscaling.

The rainfall data for both reference (1974-2018) and projected period (2019-2098) for the selected models are analyzed. The future period is divided into two separate sub-periods corresponding to the years 2019-2058 and 2059-2098. This division was applied for two reasons: (1) the intensity of the precipitation and the duration of wet and dry periods changes significantly after 2060 and (2) at least 40

years of observed data are required to reliably calibrate the LARS-WG generator. Eventually, there is one time series for the reference period, and six time series referring to the projected time period (2019-2098), two per RCP, which are used as input for the LARS-WG.

2.6 Monte Carlo Simulations and methods for results analysis

The six time series derived from the emission scenarios along with the reference period time series, are stochastically modeled using the LARS-WG. In order to select the optimum number of Monte Carlo simulations, we experiment with different numbers (10, 15, 30, 60, 90, 120, 170, and 220) of rainfall realizations and at the same time we check if the range of values of the simulated monthly time series contains at least 95% of the values of the original time series [34]. The respective percentage for each number of realizations is given respectively by 85.6%, 88.8%, 95%, 97.7%, 97.9%, 98.1%, 99.1%, and 99.4%. To reduce the overall computational time, the smallest number of realizations meeting the 95% inclusion criterion, i.e., 30 realizations, is used in the analysis (as in [22])

The reference period rainfall is also simulated by the LARS-WG, generating 30 realizations which are run by the SWAT model to determine the reference period variability of total flow and nitrate and sediment concentration. The means of the 30 realizations (plus the original downscaled time series) of every variable, scenario and time window, are tested under the Kolmogorov-Smirnov test combined with the bootstrap methodology [35, 36] at the 5% significance level to assess whether the samples can be approached by normal distributions, in order to better portray the results (see section 3.1).

3. Results

3.1 Rainfall and flow results analysis

For each scenario and time window, the mean and standard deviation of the observed and simulated monthly values are compared. Although the model succeeds in portraying the monthly means, in some cases the standard deviation of the rainy months is underestimated by the simulations. A methodology to overcome this underestimation of the variance was developed in [22]. A linear transformation is therefore applied to those time series that are not adequately simulated by the LARS generator. This methodology eventually generates corrected time series with the same properties (mean and variance) as the original sample (see [22] for the detailed description and Supplementary Material equations).

The time series of the total flow generated from the SWAT model are produced as described in section 2.3 for each sub-period (i.e. 2019-2058 and 2059-2098). The results for rainfall and flow can be found in [22] and here the annual time-series are graphically depicted in Fig.5. The flow estimate was converted from cubic meters per second into equivalent runoff depth per year with reference to the area of 211.8 km², which includes the main basin and the extended karstic area. An analysis regarding the uncertainty in monthly rainfall and flow has been carried out [22], according to which the rainfall uncertainty of the rainy months (October, November, December, January, February, March) is lower than the uncertainty of the drier ones (April, May, June, July, August, September), since the monthly values of dry months can range from zero rainfall to large monthly values.. This rainfall uncertainty is translated to ranges from 19.7 to 123.9 mm for the wet months and from 0.6 to 35.5 mm for the dry months. It is also noteworthy, that the uncertainty of flow is generally lower than the uncertainty of rainfall for the months January, February, March, April, May, June, July and August, but increases and exceeds the rainfall uncertainty values for the rest of the months (September, October, November and December). This is due to the way that the rainfall is distributed inside each month under consideration. Firstly, during the summer months (June, July and August), which have monthly rainfall values equal or close to zero, the flow is constantly low with no significant variations. Then, if the daily rainfall in the following months (mainly September and October, which have intermediate monthly rainfall values), takes place during successive days within the month, then the respective flow values increase compared to the low summer flows, and if the daily rainfall is dispersed in the month, then the impact on the flow is minimal, due to the dry conditions which preceded it (the low rainfall amounts are mostly absorbed by the soil, without forming significant flow). Thus, there is high variability in flow for the months following the summer season, until the wetter months take over, and the intra-monthly flow stabilizes. The flow uncertainty is translated to ranges from 6.8 to 93.1 mm for the wet months and from 0.5 to 29.4 mm for the dry months. For the months of September, October, November and December, the high percentages of uncertainty are translated to flow ranges from 1.17 mm to 93.1 mm.

The means of the 30 realizations (plus the original time series) of each scenario and time window, for total flow, are tested under the Kolmogorov-Smirnov (KS) test combined with the bootstrap method [35, 36]at the 5% significance level. A "P" value of bootstrap KS test bigger than 0.05 means that the distribution passes the goodness-of-fit test at 5% significance level. According to the test, the hypothesis that the samples come from normal distributions can be accepted for all the time series tested. Therefore, for each scenario, the estimation of the 95% range is possible, by adding and subtracting 2 standard deviations on the mean of the realizations. The mean and range for each of the three scenarios, RCP2.6, RCP4.5 and RCP8.5 for the two projected 40-year periods and for the reference period can be summarized in Table 1. The internal variability of the reference period is in the 752.7-930.9 mm/year range (159.4-197.2 hm³/year). This range overlaps with the RCP8.5 scenario for the 2019-2058 window (721.4-873 mm/year), indicating that RCP8.5 does not predict significant flow decrease for this period. More specifically, the RCP8.5 scenario predicts a mean decrease of -5.3 % with a range of -14.3% to +3.7 %, compared to the reference period. The RCP4.5 scenario predicts a mean -16.7% decrease ranging from -27.0 % to -6.3% and the RCP2.6 scenario predicts an increase of 32.1% with a range of 19.7% to 44.4%. After 2059, the respective changes are as follows: decrease from -47.5% to -33.0% (RCP8.5 scenario), decrease from -27.6% to -10.1% (RCP4.5 scenario), and increase ranging between 24.6% and 61.1% (RCP2.6 scenario).



Fig.5 Total exit flow predictions for each climate change scenario: (a) RCP2.6, (b) RCP4.5 and (c) RCP8.5 for the time period 2019 to 2098. The original time series (based on the climate scenario rainfall forecasts) is shown by the solid line. The 90% confidence interval (CI) of the predicted flow values (based on the simulated realizations) is shown by the dashed (5% percentile) and dotted (95% percentile) lines

Table 1.	The mean and the 95% range for rai	nfall and total flow b	ased on the simulation	of rainfall according to the	ne three climate change
scenarios	8.				

	1974-2018	2019-2058			2059-2098		
variable	reference per.	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
rainfall	1120.6 ± 78.4	1426.9 ± 99.2	1008.8 ± 84.3	1107.3 ± 71.9	1507.9 ± 135.9	999.8 ± 72.9	829.8 ± 69.3
total flow (mm/year)	841.8 ± 89.1	1111.9 ± 104.0	701.5 ± 87.0	797.2 ± 75.8	1202.4 ± 153.5	682.9 ± 73.6	503.2 ± 61.2

3.2 Sediment and Nitrate mass results analysis

The sediment and nitrate mass are estimated by multiplying the daily concentration values at the basin exit with the corresponding flow values. The daily values are transformed to monthly and annual values for further analysis. The annual time series of the present and projected time series for the variables of sediment and nitrate export along with the 95% Confidence Interval range of the iterations is presented in Fig.6.

The means of the 30 realizations (plus the original time series) of each scenario and time window, for sediment and nitrate mass, are again tested under the Kolmogorov-Smirnov (KS) test combined with the bootstrap method [35, 36] at the 5% significance level and hypothesis that the samples come from normal distributions can be accepted for all the time series tested. The mean and range for each of the three scenarios, RCP2.6, RCP4.5 and RCP8.5 for the two projected 40-year periods and for the reference period can be summarized in Table 2 and the distributions are presented in Fig.7.

When comparing Figures 5 and 6 (nitrate simulation), it is obvious that the nitrate mass follows the patterns of flow, as the nitrogen transfer is relatively proportional to runoff. The sediment amount, on the other hand, although follows the trends defined by precipitation and flow, has a more random behavior.

The quantification of the uncertainty of the average 40-year nitrate and sediment mass export can be assessed as a ratio of the 5–95 percentile range by the respective annual mean over the 40-year period. Thus, for the 2019-2058 period, the uncertainty of the average 40-year nitrate mass at the exit of the river basin is 14.9%, 16.1% and 15.3% for RCP2.6, RCP4.5 and RCP8.5 respectively. These percentages change to 18.7%, 19.6% and 17.1% during the 2059-2098 period. The uncertainty of the total sediment is higher, as for the 2019-2058 period the uncertainty is 25.9%, 44.9% and 30.7% (RCP2.6, RCP4.5 and RCP8.5 respectively) and for the 2059-2098 the uncertainty of each RCP is 34.9%, 50.4% and 42.9%. The ranges of uncertainty for flow and nitrate mass are similar (17-20%), however, this percentage is significantly higher for the case of sediment mass, due to the complexity of the erosion process: sediment erosion and transport is affected by a greater number of factors, such as the duration of dry periods which make sediment more erodible and thus easily transferred during the subsequent wet period.



Fig.6 Annual sediment and nitrate export mass predictions for each climate change scenario: (a) RCP2.6, (b) RCP4.5 and (c) RCP8.5 for the time period 2019 to 2098. The original time series (based on the climate scenario rainfall forecasts) is shown by the solid line. The 90% CI of the predicted flow values (based on the simulated realizations) is shown by the dashed (5% percentile) and dotted (95% percentile) lines

Table 2. Mean and 95% reference range for total sediment and nitrate mass according to the iterations of the three climate change scenarios for the present-reference period and for the two future periods

variable	1974-2018	2019-2058			2059-2098		
	reference per.	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Sediment	10645.7 ± 5909.9	29919.1 ±	9885.7±	$15540.9 \pm$	$39998.4 \pm$	$15397.8 \pm$	$10656.5 \pm$
mass (t)		10562.2	6017.1	6439.4	18211.4	11197.2	6091.1
Nitrate mass (t)	141.5±35.4	228.6 ± 47.7	130.4 ± 32.3	159.8 ± 31.6	169.6 ± 40.1	97.2 ± 27.6	82.5 ± 18.6



Fig.7 Probability density functions of the exported nitrate mass and sediment mass (based on 30 realizations and the original time series for the respective climate change scenario) for the (a) 2019-2058 and (b) 2059-2098 period, plotted for the RCP2.6, RCP4.5 and RCP8.5 scenario

Exported sediment mass is expected to increase for all climate change scenarios and both future periods with the exception of the RCP4.5 scenario and the 2019-2058 period and RCP8.5 scenario and the 2059-2098 period, during which the sediment mass is not expected to change significantly compared to the reference period. Nitrate mass follows the pattern of flow and fluctuates with it.

The range of the of the mean monthly sediment and nitrate mass values (95% confidence interval) of the 30 realizations (plus the original time series) is computed and divided by the average of the mean for each month (the result is expressed as a percentage). Results are shown in Fig.8. The monthly uncertainty of nitrate mass again complies with the monthly uncertainty of flow [22]. This nitrate mass export uncertainty is translated to ranges from 2.1 to 21.9 t for the wet months and from 0.1 to 13.5 mm for the dry months. Uncertainty in monthly sediment mass export is lower during the wet months of January, February, November and December and the dry month of July. During these months the rainfall and flow are stabilized and so is the erosion process. The uncertainty reaches the highest values during September and October, following the uncertainty in flow predictions (section 3.1), and occasionally during the months before summer (May, June), when the rainfall uncertainty is becoming significant. The range of these uncertainties in terms of mass is 0.6 to 12662 t.



Fig.8 Graphical representation of the mean monthly sediment and nitrate values (solid lines - left y axis) and the % uncertainty expressed as the 95% range divided by the average variable values (dotted lines - right y axis), as estimated by the 30 realizations (plus the original time series) of precipitation and simulated flow using the SWAT model.

4. Discussion and Conclusions

This study focuses on assessing the role of uncertainties on the flow and water quality estimates in a karstic Mediterranean watershed with semi-arid climate. In particular, we concentrate on the uncertainties stemming from the Karst-SWAT input rainfall time series, based on future climate change projections. We derive estimates of the total watershed flow, exported nitrate and sediment mass, as well as a range of probable values that encompass the impact of uncertainty. The study aims to provide information on the mean and internal variability or stochastic uncertainty of specific RCPs for two non-overlapping periods in the future (2019-2058 and 2059-2098). We are not concerned with the selection of the optimal climate change model, but rather with assessing the uncertainty of the hydrologic model outcomes, given typical climate change model time series, nor do we deal with the uncertainty stemming from hydrologic model selection. Our model, also, does not take account for the presence of potential trends in the precipitation time series. However, as we are interested in simulating the average statistical features of the 40-year periods and not the temporal evolution, it is not necessary to explicitly model the trend function. The quantification of model parameter uncertainty was not dealt in this study, as Nikolaidis et al. [12] have already conducted a sensitivity and uncertainty analysis due to model parameters on the specific model setup, using the @RISK software by PALISADE, after the karst model parameters were calibrated. By running 1000 Monte Carlo simulations, they calculated that the uncertainty (95% confidence level) of the simulation results (karstic flow) due to karstic model parameters ranged from 0.2% to 5.8% on the monthly average discharge. This percentage is negligible compared to the monthly uncertainty stemming from internal variability (24.5% to 200%). The uncertainty (95%

confidence level) of the simulation results of nitrate concentrations due to the four hydrologic parameters and one chemical parameter was also very low and on average 0.12% of the monthly average nitrate concentration.

The study reveals that the internal variability (or stochastic uncertainty) inherent in precipitation time series predicted by climate change time scenarios is propagated to estimates of flow, sediment and nitrates, to a greater extend compared to model parameter uncertainty. The mean annual internal variability of the emission scenarios, for the future 40-year periods is on average 15.3 % for rainfall, 22.3 % for total flow, 17% for the exported nitrate mass, and 38.3% for the exported sediment mass. These values correspond to the ratio of the 5–95 percentile range divided by the respective annual mean over the 40-year period. The results do not vary significantly between the emission scenarios. The rainfall uncertainty range is always lower compared to the uncertainty range of total flow; on average the uncertainty range of total flow is 30% higher than that of rainfall. Also, the uncertainty range of nitrate mass is 30% lower than that of the total flow (approximates rainfall), and the two uncertainties are linearly related.

The results regarding the comparison of the distributions of the 40-year means for all scenarios, point out that 2019-2058 will be a transition period, during which the outcomes of different climate scenarios overlap due to the domination of internal variability, and the changes in flow (and nitrates) are not as significant as the ones forecasted after 2060, when the choice of the emission scenario becomes more important. Northrop and Chandler [37] also came to a similar conclusion using Bayesian analysis on models obtained from phase 3 of the Coupled Model Intercomparison Project (CMIP3). During this transition period, important decisions should be taken regarding the water management of the area, in response to the climate trends that will be observed. The projected impact of climate change at the Koiliaris River, and the island of Crete in general, changes significantly as a function of the emission scenario realized (a statement also supported by Joseph et al. [38]), and ranges from significant flow increases (RCP2.6) to significant decreases in runoff.

The study revealed that the inherent (or stochastic) uncertainty which exists in climate change time series of precipitation, is propagated to a large extend on the total flow and the sediment and nitrate export of the basin. It is not possible to conduct a uniform conclusion regarding flow from multiple RCMs but it is highly important that their stochastic uncertainty is taken under consideration when planning for water resources adaptation and mitigation measures, in order to alleviate climate change impacts, as the uncertainty range may reveal possible deficits that were not otherwise taken into account. Finally, it is noteworthy, that sediment transport is expected to increase, regardless of the trend of flow and the high uncertainty of the variable, due to the fact that drought makes soils more susceptible to erosion, therefore measures for the limitation of poor agricultural practices and the protection of the vulnerable areas should be taken promptly.

The methodology presented in this paper combines the advantages of stochastic climate change scenarios with those of a fully integrated hydrologic model. The integration of surface and subsurface flow in the same model provides more realistic simulations of water cycle and improved representation of groundwater recharge, which is important for impact assessment on groundwater resources. This is the first time, to our knowledge, that an assessment of internal variability is applied to a karstic Mediterranean watershed. The Koiliaris River Basin can represent a benchmark for comparative studies in other similar regions of the globe.

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References

[1] Zhang, R., Corte-Real, J., Moreira, M., Kilsby, C., Birkinshaw, S., Burton, A., Fowler, H.J., Forsythe, N., Nunes, J.P., Sampaio, E., dos Santos, F.L., Mourato, S.: Downscaling climate change of water availability, sediment yield and extreme events: Application to a Mediterranean climate basin. Int. J. Climatol. 39, 2947–2963 (2019)

[2] Nerantzaki, S.D., Giannakis, G. V., Nikolaidis, N.P., Zacharias, I., Karatzas, G.P., Sibetheros, I.A.,: Assessing the Impact of Climate Change on Sediment Loads in a Large Mediterranean Watershed. Soil Sci. 181, 306–314 (2016)

[3] Nerantzaki, S.D., Giannakis, G.V., Efstathiou, D., Nikolaidis, N.P., Sibetheros, I.A., Karatzas, G.P., Zacharias, I.: Modeling suspended sediment transport and assessing the impacts of climate change in a karstic Mediterranean watershed. Sci. Total Environ. 538, 288-297 (2015)

[4] Bussi, G., Francés, F., Horel, E., López-Tarazón, J.A., Batalla, R.J.: Modelling the impact of climate change on sediment yield in a highly erodible Mediterranean catchment. J. Soil Sediment. 14, 1921–1937 (2014)

[5] Bangash, R.F., Passuello, A., Sanchez-Canales, M., Terrado, M., López, A., Elorza, F.J., Ziv, G., Acuña, V., Schuhmacher, M.: Ecosystem services in Mediterranean river basin: Climate change impact on water provisioning and erosion control. Sci. Total Environ. 458–460, 246–255 (2013)

[6] Maas, G.S., Macklin, M.G.: The impact of recent climate change on flooding and sediment supply within a Mediterranean mountain catchment, southwestern Crete, Greece. Earth Surf. Proc. Land. 27, 1087–1105 (2002)

[7] Mas-Pla, J., Menció, A.: Groundwater nitrate pollution and climate change: learnings from a water balance-based analysis of several aquifers in a western Mediterranean region (Catalonia). Environ. Sci. Pollut. R. 26, 2184–2202 (2019)

[8] Lutz, S. R., Mallucci, S., Diamantini, E., Majone, B., Bellin, A., Merz, R.: Hydroclimatic and Water Quality Trends across Three Mediterranean River Basins, Sci. Total Environ., 571, 1392–1406 (2016)

[9] Hartmann, A., Goldscheider, N., Wagener, T., Lange, J., Weiler, M.: Karst water resources in a changing world: Review of hydrological modeling approaches. Rev. Geophys. 52, 218–242 (2014).

[10] Pachauri, R.K., Meyer, L.A... van Ypserle, J. P.: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland, IPCC, 151 p. (2014)

[11] Moraetis, D., Efstathiou, D., Stamati, F., Tzoraki, O., Nikolaidis, N.P., Schnoor, J.L., Vozinakis, K.: High-frequency monitoring for the identification of hydrological and bio-geochemical processes in a Mediterranean river basin. J. Hydrol. 389(1-2), 127-136 (2010)

[12] Nikolaidis, N.P., Bouraoui, F., Bidoglio, G.: Hydrologic and Geochemical Modeling of a Karstic Mediterranean Watershed, J. Hydrol., 477, 129–138 (2013)

[13] American Society of Civil Engineers. Task Committee on Hydrology Handbook. Hydrology handbook (2nd ed). ASCE, New York (1996)

[14] Jacob, D., Elizalde, A., Haensler, A., Hagemann, S., Kumar, P., Podzun, R., ... Wilhelm, C.: Assessing the transferability of the regional climate model REMO to different coordinated regional climate downscaling experiment (CORDEX) regions. Atmosphere. 3(1)181–199 (2012)

[15] Semenov, M.A., Stratonovitch, P.: Use of multi-model ensembles from global climate models for assessment of climate change impacts. Clim. Res. 41(1), 1-4. (2010)

[16] Semenov, M.A., Brooks, R.J., Barrow, E.M., Richardson, C.W. Comparison of the WGEN and LARS-WG stochastic weather generators for diverse climates, Clim. Res. 10(2), 95–107 (1998).

[17] Racsko, P., Szeidl, L., Semenov, M.A. A serial approach to local stochastic weather models, Ecol. Model., 57(1-2), 27-41 (1991).

[18] Bailey, N. T. J.: The Elements of Stochastic Processes with Applications to the Natural Sciences. Wiley, New York (1964)

[19] Richardson, C. W.: Stochastic simulation of daily precipitation, temperature, and solar radiation. Water Resour. Res. 17(1), 182-190 (1981)

[20] Richardson, C.W. Wright, D.A.: WGEN: A Model for Generating Daily Weather Variables. US Department of Agriculture, Agricultural Research Service, ARS-8, United States Department of Agriculture, Agricultural Research Services, Washington DC, p. 83 (1984)

[21] Mehan, S., Guo, T., Gitau, M.W., Flanagan, D.C.: Comparative Study of Different Stochastic Weather Generators for Long-Term Climate Data Simulation. Climate, 5(2), p. 26 (2017)

[22] Nerantzaki, S.D., Nikolaidis, N.P, Hristopulos, D.T.: Estimation of the uncertainty of climate change hydrologic predictions at a karstic Mediterranean watershed. Vadose Zone J. Under Review

[23] Box, G., Jenkins, G.: Time Series Analysis: Forecasting and Control. San Francisco: Holden-Day (1970)

[24] Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R.:. Large area hydrologic modeling and assessment Part I: Model development., J. Am. Water Resour. As., 34(1), 73-89 (1998)

[25] Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R.: Soil and Water Assessment Tool Theoretical Documentation Version 2009. Texas Water Resources Institute, Texas (2011)

[26] Tzoraki, O., Nikolaidis, N. P.: A generalized framework for modeling the hydrologic and biogeochemical response of a Mediterranean temporary river basin. J. Hydrol., 346(3), 112-121 (2007)

[27] Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., Veith, T. L.: Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. T. ASABE, 50, 885–900 (2007)

[28] Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O.B., Bouwer, ... Yiou, P.: EURO-CORDEX: new high-resolution climate change projections for European impact research, Reg. Environ. Change, 14(1-2), 563–578 (2014)

[29] Taylor, K. E., Stouffer, R.J., Meehl, G.A.: An Overview of CMIP5 and the Experiment Design, B. Am. Meteorol. Soc., 93(4), 485–98 (2012)

[30] Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., ..., Wilbanks, T.J.: The next generation of scenarios for climate change research and assessment. Nature, 463, 747–56 (2010)

[31] van Vuuren, D.P., Lucas, P.L., Hilderink, H.: Downscaling drivers of global environmental change: Enabling use of global SRES scenarios at the national and grid levels. Global Environ. Chang., 17(1), 114-130 (2007)

[32] O'Neill, B.C., Kriegler, E., Riahi, K., Ebi, K.L., Hallegatte, S., Carter, T.R., ... van Vuuren, D.P., (2013). A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Climatic Change, 122(3), 387–400. doi:10.1007/s10584-013-0905-2

[33] Grillakis, M.G., Koutroulis, A.G., Tsanis, I.K.: Multisegment statistical bias correction of daily GCM precipitation output. J. Geophys. Res.-Atmos., 118(8), 3150–3162 (2013)

[34] Gilman, M. J.: A Brief Survey of Stopping Rules in Monte Carlo Simulations, Proceedings of the Second Conference on Applications of Simulations (Winter Simulation Conference, 1968), 16–20. New York, New York, USA (1968)

[35] Clauset, A., Shalizi, C., Newman, M.: Power-Law Distributions in Empirical Data. SIAM Rev. 51(4), 661-703 (2009)

[36] Wang, C., Zeng, B., Shao, J.: Application of bootstrap method in Kolmogorov-Smirnov test. International Conference on Quality, Reliability, Risk, Maintenance, and Safety Engineering 2011, 287–291. Xi'an, China. (2011)

[37] Northrop, P.J., Chandler, R.E.: Quantifying Sources of Uncertainty in Projections of Future Climate. J. Climate, 27, 8793–8808 (2014).
[38] Joseph, J., Ghosha, S., Pathak, A., Sahai, A.K.: Hydrologic impacts of climate change: Comparisons between hydrological parameter uncertainty and climate model uncertainty. J. Hydrol., 566, 1-22. (2018)