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Sediment transport in the Koiliaris river of Crete

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Abstract

In this paper, a study of the sediment transport in a complex Mediterranean watershed (i.e. the Koiliaris River Basin of Crete) consisting of temporary flow tributaries and karstic springs is presented. Both daily flow data (2005-2013) and monthly sediment concentration data (2011-2013) were used to calibrate the modified Soil and Water Assessment Tool (SWAT) model, designed to simulate the hydrology, sediment yield and water quality of ungauged watersheds, and augmented with a karst flow model in order to simulate the contribution of the extended karst to the spring discharge in the basin. The results showed good agreement between observed and model values for both flow and sediment concentration. However, since no data representative of high sediment concentration conditions were available, such as during extreme flow events, an automated sediment sampling device (Sediment Trap), which allows for flow weighted sampling, has been developed and is detailed in this paper. This device is undergoing testing to ensure it can provide accurate estimates of sediment yield, especially during a flush flood event when large amounts of sediment are carried downstream. The sediment measurements will then be used to calibrate and verify the sediment transport simulations of the Koiliaris River watershed generated by the SWAT model. The sediment transport simulations and the development of the automated sampling device were part of the preliminary work for the pilot application of the "Cybersensors" infrastructure in the Koiliaris River. The Cybersensors research project aims to develop an intelligent integrated monitoring system, which will utilize electrochemical and optical sensors, and will allow for high-frequency monitoring of the physical and chemical parameters of a river flow and thus the rapid detection of environmental change during episodic events, as well as for long term monitoring.

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Keywords: Mediterranean watershed; sediment transport; SWAT Model; karst flow model; sediment trap device; turbidity

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1. Introduction

The research project "Cybersensors" (High Frequency Monitoring System for Integrated Water Resources Management of Rivers) aims to develop and implement an intelligent, integrated environmental data collection system, combining high frequency monitoring and real-time observing systems for the quantification of the hydrologic and geochemical processes that take place in Mediterranean watersheds, which are characterized by variable temporal and spatial scales. The monitoring system will utilize optical and electrochemical sensors, for the physical parameters (i.e. flow, suspended solids, and temperature) and chemical parameters (i.e. conductivity, dissolved oxygen, nitrates, pH and heavy metals) of the river. Data from the optical sensors will be analyzed in-situ with special pattern recognition algorithms, in order to estimate the velocity field and the total discharge of the river flow, as well as the distribution of suspended solids using the hue values of the pictures. The Cybersensors system will be comprised of the sensors, CPU units, storage devices and a telecommunication system for data transmission. The system will be sending only the required processed data, rather than raw data, to a central station where the data will be used in an on-line integrated water resources management model. Thus, events of short duration and high intensity, such as "first flash" floods, which transfer large quantities of sediments and pollutants in both urban and rural areas will be adequately monitored and recorded [1].

The Cybersensors infrastructure will be tested in two pilot applications in Koiliaris River of Crete, and Acheloos River of Western Greece. The system will be deployed for extended periods at Koiliaris River and during a two week field campaign to Acheloos River. The system deployment at Koiliaris River will be used to collect data for the calibration of model simulations of the hydrology and sediment transport of the Koiliaris River watershed, as well as for the modeling of bank erosion. In this study, preliminary work on the Koiliaris pilot application is presented. Specifically, daily flow data (2005-2013) and monthly sediment concentration data (2011-2013) were used to calibrate discharge and sediment concentration simulations by the modified Soil and Water Assessment Tool (SWAT) model. The latter is designed to simulate the hydrology, sediment yield and water quality of ungauged watersheds [2], but for the Koiliaris watershed case it is augmented with a karst flow model in order to simulate the contribution of the extended karst to the spring discharge in the Koiliaris basin [3].

Since the available sediment concentration data from grab samples were limited to low concentration values and there were no data available during flood conditions, and thus high sediment concentration simulations could not be adequately calibrated, an automatic suspended sediment sampler has been developed and is detailed in this paper. The automatic sampler works as follows: water specimens are pumped during storm events and the pump rotation is proportional to the stage, allowing for a flow weighted sampling. Sediment sampling is initiated automatically when water surpasses a certain level, and/or when turbidity surpasses a certain threshold. The water then passes through a sediment trap (5 micron filter) that captures the sediment. The solids are weighted once a week or after each storm and the data are converted into a total sediment flux. The sediment sampler, which is an important component of the Cybersensors infrastructure, is currently undergoing testing to ensure its operational robustness, particularly under harsh environmental conditions.

2. Koiliaris River Basin

The area under study is Koiliaris River Basin, situated 15 km east of the city of Chania, in Crete. The basin area is about 130 km^2, with altitudes between 0 and 2120 m MSL. Geologically, the area is characterized by the limestone – karstic system in the south part which lies beneath impermeable deposits of marbles and schists in the northern part, which also includes alluvial deposits. The total length of the river is 36 km. Koiliaris is joined with four tributaries, from which two are temporary rivers (Keramianos and Anavreti) and two are permanent ones. There are three telemetric hydrometric stations and three telemetric meteorological stations inside the basin, as shown in Fig. 1, while there are two hydrometric stations outside the basin, one in the extended karstic area. Data at each station are recorded every 5 minutes [4].

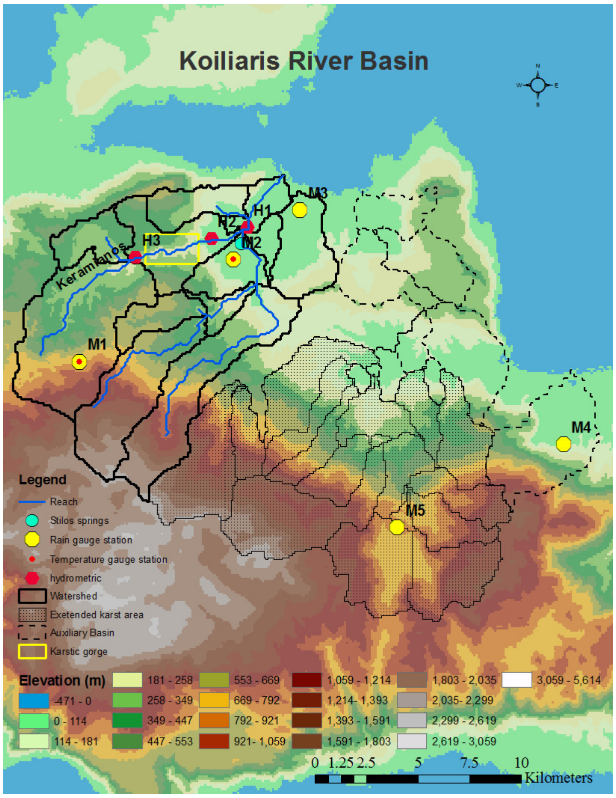


Fig. 1. Koiliaris River Basin and hydrometeorological network.

2.1. Peculiarity of Koiliaris Watershed

Karst systems in the Mediterranean region have the special feature that a spring could receive contributions from the karst that is extended outside the watershed boundaries to which the spring belongs or karst situated one on top of another with different hydraulic characteristics and thus different transmissivities [5]. This fact underlies the importance of the identification of the extended karst area that contributes to the flow of a spring for the acquisition of accurate hydrologic and geochemical balances of the system [4,6,7]. In our case, the karst system is characterized by fast infiltration and direct connection to the conduits below. There are two main series of springs in which the karst system discharges: Stilos springs at elevation +17 m a.m.s.l. and an intermittent spring, Anavreti at +24 m a.m.s.l. Both of them later feed Koiliaris River. The total recharge area of the springs extends beyond the boundaries of Koiliaris River Basin to the southeast of the watershed boundary. The geology of the region in combination with a major fault in a northeast – southwest direction directs the water towards the springs in the Koilaris River Basin [7].

3. SWAT model

SWAT is a watershed scale, continuous, long-term, distributed model designed to simulate the hydrology, sediment yield and water quality of ungauged watersheds and estimate the impact of land management practices on the hydrology, sediment, and contaminant transport in agricultural watersheds [2]. After the subdivision of the watershed into different sub-basins connected by a stream network, the SWAT model further divides them into hydrological response units (HRUs). The model incorporates the following components: weather generator routine,

Fig. 2. Mixing of two flows: Stilos Springs with low sediment concentration (left) Keramianos tributary with high sediment concentration (right).

hydrologic mass balance, soil temperature and soil properties, plant growth, nutrients, pesticides, bacteria and pathogen mass balances, and land management practices. The hydrologic component of each HRU contains subroutines, which simulate the following processes: evapotranspiration, plant uptake, surface runoff and infiltration (using the modified Curve Number or the Green-Ampt method), percolation, lateral subsurface flow, groundwater return flow from the shallow aquifer, deep aquifer losses and channel transmission losses. Water balance is conducted for the snow compartment, soil, shallow aquifer and deep aquifer. Plant growth is based on the EPIC crop model and uses the "heat units" concept which relates crop growth to the excess of daily temperature above a base temperature. Potential evapotranspiration, leaf area index, rooting depth and soil water content determine the water uptake of plants. The SWAT system is embedded within a geographic information system (GIS) platform that can integrate various spatial environmental data including soil, land cover, climate, and topographic features.

3.1. River Flow

Due to the peculiarity of the Koiliaris watershed, an augmented version of the SWAT model, proposed by Nikolaidis et al. [3] was used, in order to simulate the contribution of the extended karst to the spring discharge and account for the variability of the discharge recession due to two karst formations. The precipitation in the karstic area of the watershed is directed to deep groundwater after SWAT simulates surface hydrologic processes such as snow accumulation and melt, surface runoff, infiltration to shallow groundwater and evapotranspiration. The deep groundwater flow from SWAT in the karstic area that could be related to a specific spring is aggregated on a daily basis and becomes the input flow to a two-part reservoir karst model. The model has already been calibrated for the Koiliaris watershed until 2010 [3], and it is further used in the current study to simulate three more years (2010-2013), for which daily flow data are available.

3.2. Sediment Concentration

Suspended sediments from Ag. Georgios hydrometric station (H1), monitored between December 2011 and February 2013 using grab samples on a monthly basis, were used for a rough calibration of the model. The sampling point is located just downstream of the cross-section, where the Keramianos tributary, primarily responsible for the sediment transport, merges with the main river, the latter being fed by the karst springs. We can assume that the flow coming from the karst springs has a constant sediment concentration equal to 3 mg/l (according to field measurements). Thus, the sediment concentration at the sampling point is equal to

$$C_{\text{sample}} = \frac{Q_{\text{karst}} * 3\,\text{mg/l} + Q_{\text{surface}} * C_{\text{surf flow}}}{Q_{\text{karst}} + Q_{\text{surf flow}}} \tag{1}$$

where Q_{karst} is the flow from the karst springs, $Q_{\text{surf flow}}$ is the surface flow from tributaries (mainly Keramianos) and $C_{\text{surf flow}}$ is the sediment concentration of the surface flow. For the sediment calibration, the sediment concentration from the model was supposed to match the observed values. In Fig 2 the mixing of the two flows of different sediment concentrations is illustrated.

4. Experimental Sampling Design

Daily rainfall and temperature data for the years 1973-2013, collected from five meteorological stations, as shown in Fig 1, were used as input to SWAT. Specifically, data from meteorological stations M3-M5 correspond to the 1973-2009 time period and since 2007, when installed, the meteorological stations M1 and M2 record rainfall and temperature every five minutes allowing for a high frequency monitoring. Stations M1 and M2 are located at 1000 and 400 m a.m.s.l. respectively. The hydrometric station H1, installed in 2004, is located just downstream of the intersection of the tributary and the main river, and includes a data logger that records stage as well as pH, dissolved oxygen, conductivity, nitrogen-nitrate concentration and water temperature at 5-min intervals. Prior to the installation of the hydrometric station, monthly flow data were available since 1973. For the verification of discharge simulation by SWAT [8], stage data from the station H1 were transformed into discharge through an equation (rating curve) developed for the specific cross-section, using flow and stage measurements conducted during the 2005-2013 period. As far as the suspended sediments are concerned, grab samples from St. Georgios hydrometric station (H1), taken on a monthly basis from 2011 to 2013, were used to calibrate the sediment concentration simulations. Water samples were filtered using pre-weighted filters, then the filters were let to dry out; the increase of each filter's weight corresponded to the suspended sediments' weight in each grab sample.

5. Results

The region surrounding Koiliaris River basin was delineated into 41 sub-basins. Koiliaris River basin has a surface area of 132 km^2 and was divided into 11 subbasins.

5.1. Discharge simulation

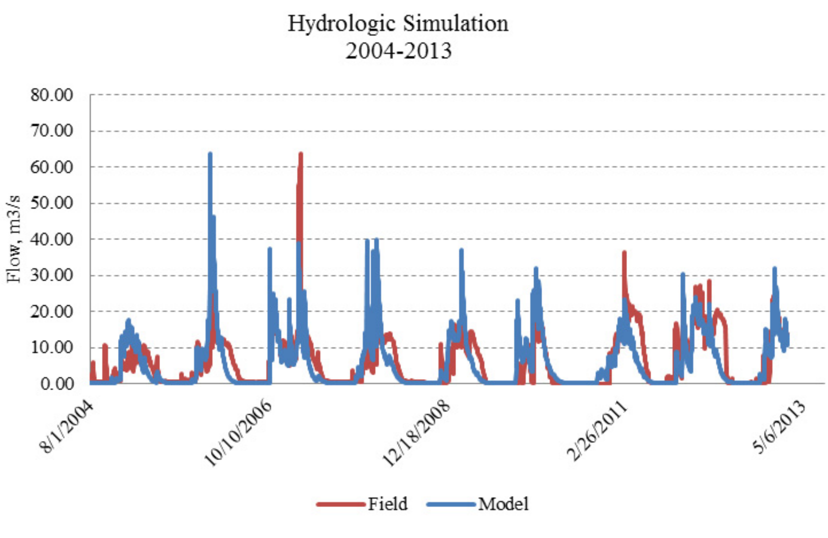


Fig 3. Hydrologic Simulation at St. Georgios station for the 2004-2013 period

SWAT was run using flow records for the 1973-2013 period. Specifically the 1973-2010 data were used to calibrate the model, whereas the 2010-2013 data were used for model validation. Fig 3 depicts simulated flows versus the observed data at Ag Georgios for the 2004-2013 period, during which continuous daily flow data were available. The simulation results suggest that the model can adequately describe the hydrology of the watershed. The goodness of fit of the calibration was tested against three statistical metrics proposed by Moriasi et al. [9]: the Nash-Sutcliffe Efficiency (NSE), Percent Bias (PBias), and RMSE Standard Deviation Error (RSR). A simulation is considered adequate if NSE > 0.5, Pbias < 25% and RSR < 0.7. For the 1973-2010 validation period, the NSE was 0.8, PBias 25.3% and RSR 0.45 for the daily records and 0.83, 23.4% and 0.41 for the monthly records, respectively. The goodness of fit of the calibration was considered adequate since all three error metrics were acceptable for both daily and monthly records. The discharge root mean square error (RMSE) was estimated to be 5.7 m^3/s and the closure of the cumulative simulated flow for the validation period and observed flow was 25%, while the correlation coefficient between observed and simulated flows was 0.62 and the slope 0.68.

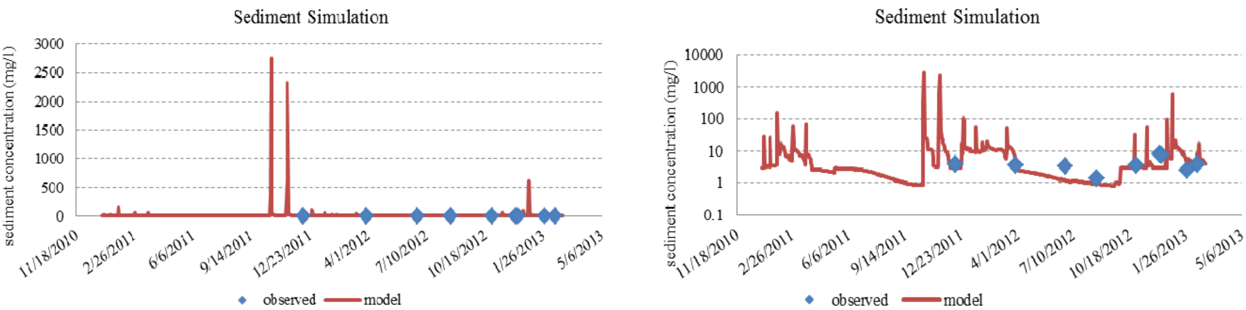
5.2. Suspended sediment simulation

Sediment concentration measurements from grab samples taken at St Georgios station (2011-2013) were used for the calibration of the model's sediment concentration simulations. There is good agreement between simulated and observed concentration values as depicted in the semi-logarithmic diagram of Fig 4, considering that the available concentration data were limited to low concentration values and there were no data available during flood conditions. However, it is a fact that, almost twice a year, during flood conditions, Keramianos tributary transfers significant loads of suspended sediment, due to the high levels of erosion of the schist formations where the tributary flows over initially, before it enters a karstic gorge. With no concentration data available from flood events, we could only have an approximate value of high sediment concentration at our disposal, by considering approximately equal extreme sediment concentration value with the one of Vivari station in Evrotas (3000 mg/l) [10]. The objective was to calibrate the sediment in such a way that high suspended sediment concentrations (originating from the subbasins with schist formations) would be simulated, and at the same time, the model output would match the available low concentration values, using equation 1.1. The simulation had an RMSE of 3.7 mg/l, which is considered satisfactory, taking into account the magnitude of the sample, as well as the lack of measured extreme sediment concentration values.

6. Sediment trap

6.1. Motivation

As mentioned in the previous section, adverse field conditions do not allow for sediment measurements (using grab samples) to be conducted during periods of high sediment concentrations, such as flash floods, or first flush events in temporary rivers, when most of the annual suspended sediment is usually transported. Automatic measuring of suspended sediment concentration (SSC) is thus preferable over grab sampling or other methods of Fig



4. (a) Sediment simulation at Ag. Georgios station for the 2011-2013 period (b) Semi-log plot.

manual collection of suspended sediment, but the high frequency sampling necessary during extreme events, is expensive and impractical if performed continuously. Thus, an ideal method would be the continuous measuring of water discharge and the occasional discrete sampling of water specimens for suspended sediment concentration analysis. Sampling can be triggered by surrogate variables which are monitored in situ by sensing devices and can provide important information concerning the variable of interest. In 1996 Lewis was one of the first researchers to use turbidity as an auxiliary variable to activate a pumping sampler for the estimation of suspended sediment concentration [11]. According to Gippel [12], field turbidity is an adequate indicator for sediment concentration in most cases. In fact, turbidity peaks during floods usually arrive before flow peaks in an erodible basin, making turbidity a better predictor than water discharge [13]. Thus, turbidity monitored in situ by sensing devices can provide the trigger for sampling to commence [11]. In our case it works as follows: when a certain threshold of rising or falling turbidity is reached, the programmable data logger instructs an automatic pumping sampler to collect a sample. The pumped specimens are analyzed in the laboratory for suspended sediment concentration. The method results in full description of the variation of sediment loads during a flash flood event.

The proposed automatic sediment sampling system is being implemented at St. Georgios River Gauging Station, where the Hydrometric station H1 is installed, as shown in Figure 1. As mentioned earlier, gauging station H1 was located just downstream of the merge of the two flows; the permanent one from Stilos springs and the temporary one from Keramianos tributary. The channel at this point is about 8.5 m wide with an average depth of 0.70 m.

6.2. System Architecture

Water specimens are pumped during storm events and the pump rotation is proportional to the stage, allowing for a flow weighted sampling. Water is imported from an intake nozzle which is designed to be positioned at 60% of the flow depth for a representative sample [14]. Sampling is initiated automatically when at least one of the two conditions below holds:

- Water surpasses a certain level: A micro-controller collects river stage data in real time from a level logger and converts them to flow. This is possible with the utilization of the rating curve for the specific site (water level – discharge relationship). Based on flow measurements conducted from 2004 to 2013, a two-part rating curve has been defined: When the water level H at hydrometric station H1 is lower or equal to 0.5 m then the flow discharge is computed using the expression:

$$Q = 0.35H \;\left(m^3/s\right) \tag{2}$$

When the water level H at H1 is over the 0.5 m mark, then the flow discharge is given by

$$Q = 36.33H - 17.3 \;\left(m^3/s\right) \tag{3}$$

The rating curve is being continuously updated.

- Turbidity surpasses a certain threshold (thus signaling a flood event): Turbidity is constantly recorded at the station by the turbidity sensor of the Multi-Parameter Water quality TROLL 9500, of In-Situ Inc.

The water sample then passes through a sediment trap (5 micron filter) that captures the sediment (Fig. 5). The solids are weighted once a week or after each storm and the data are converted into the total suspended sediment flux as follows:

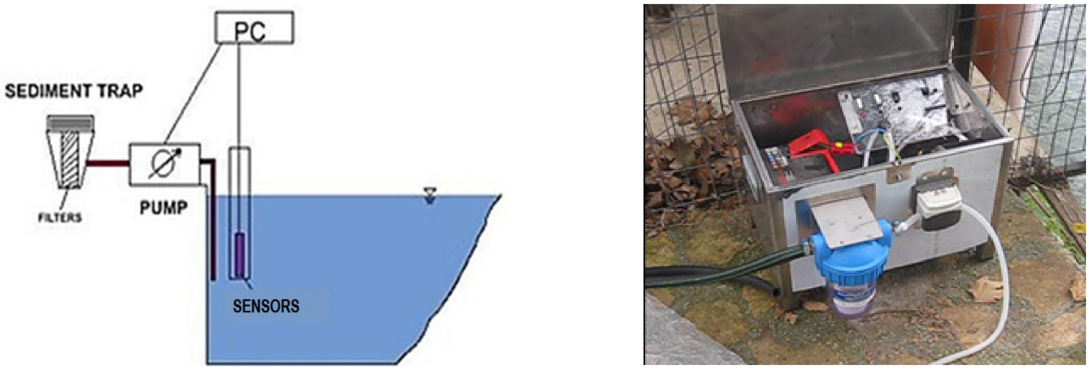


Fig 5. (a) Sediment trap setup (b) Sediment trap prototype photo

If M_{filter} is the suspended sediment mass captured by the filter and q_{pump} is the pump rate, the total sediment mass during a flood can be estimated by

$$M_{\text{total}} = M_{\text{filter}} \cdot \frac{\sum V}{\int q_{\text{pump}} \mathrm{d}t} \tag{4}$$

where ΣV is the total water volume during a flood event, as estimated by the stage at each interval. We can then have a rough estimate of the mean suspended sediment concentration during the flood event:

$$\overline{s} = \frac{M_{\text{total}}}{\sum (Q \Delta t)} \tag{5}$$

The automatic sampling system is currently undergoing testing to ensure it can function under severe conditions.

7. Conclusions

A preliminary study of the hydrology and sediment transport in Koiliaris River of Crete has been successfully performed. It involved flow and sediment concentration simulations provided by SWAT model augmented with a two-reservoir karst model, which were calibrated against extensive flow records and shorter sediment concentration records. The latter contained data from grab samples taken during normal flow conditions with low sediment concentrations, and were thus not representative of the sediment concentrations during flash flood conditions. To rectify this sampling shortcoming, an automatic sediment sampler has been developed, which collects flow-weighted water samples containing suspended sediment, triggered by either water stage, and/or turbidity.

The automatic sampler is undergoing testing, before it is permanently deployed at a specific location along Koiliaris River. It will then become part of the Cybersensors infrastructure, which will allow for adaptive and high frequency environmental sampling, supported by several electrochemical and optical sensors, CPU units, storage devices and a telecommunication system for data transmission.

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