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Water and sediment transport modeling of a large temporary river basin in Greece

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HIGHLIGHTS

- We studied the spatial distribution of runoff and sediment of a large river basin.
- The developed methodology constrained the parameter values of the hydrologic and sediment simulation.
- Model simulation of hydrology and sediment was in good agreement with field data.
- During a dry year 77% of the river segments dried out while during a wet year 51% of the river segments dried out.
- The average sediment yield for the whole watershed was 0.85 t ha^{-1} yr^{-1} (2000–2011).

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ABSTRACT

The objective of this research was to study the spatial distribution of runoff and sediment transport in a large Mediterranean watershed (Evrotas River Basin) consisting of temporary flow tributaries and high mountain areas and springs by focusing on the collection and use of a variety of data to constrain the model parameters and characterize hydrologic and geophysical processes at various scales. Both monthly and daily discharge data (2004–2011) and monthly sediment concentration data (2010–2011) from an extended monitoring network of 8 sites were used to calibrate and validate the Soil and Water Assessment Tool (SWAT) model. In addition flow desiccation maps showing wet and dry aquatic states obtained during a dry year were used to calibrate the simulation of low flows. Annual measurements of sediment accumulation in two reaches were used to further calibrate the sediment simulation. Model simulation of hydrology and sediment transport was in good agreement with field observations as indicated by a variety of statistical measures used to evaluate the goodness of fit. A water balance was constructed using a 12 year long (2000-2011) simulation. The average precipitation of the basin for this period was estimated to be 903 mm yr^{-1}. The actual evapotranspiration was 46.9% (424 mm yr^{-1}), and the total water yield was 13.4% (121 mm yr^{-1}). The remaining 33.4% (302 mm yr^{-1}) was the amount of water that was lost through the deep groundwater of Taygetos and Parnonas Mountains to areas outside the watershed and for drinking water demands (6.3%). The results suggest that the catchment has on average significant water surplus to cover drinking water and irrigation demands. However, the situation is different during the dry years, where the majority of the reaches (85% of the river network are perennial and temporary) completely dry up as a result of the limited rainfall and the substantial water abstraction for irrigation purposes. There is a large variability in the sediment yield within the catchment with the highest annual sediment yield (3.5 t ha^{-1} yr^{-1}) to be generated from the western part of the watershed. The developed methodology facilitated the simulation of hydrology and sediment transport of the catchment providing consistent results and suggesting its usefulness as a tool for temporary rivers management.

1. Introduction

Climate change is projected to impact the Mediterranean region with increasing risk of water scarcity and drought. Most climatic models predict a shift of the climate over the next century affecting the natural flow regime of rivers in the region (Klausmeyer and Shaw, 2009) and increase the spatial extent of temporary rivers and streams. Temporary

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rivers are characterized by the repeated onset and cessation of flow, and by complex hydrological dynamics in the longitudinal dimension such as advancing and retreating wetted fronts, hydrological connections and disconnections, and gradients in flow permanence, influence biotic communities and nutrient and organic matter processing (Larned et al., 2010). The extent of temporary rivers in the Mediterranean region is high while many perennial rivers become temporary during drought years due to irrigation demands of agriculture and the water needs of the industrial and domestic sectors (Tzoraki and Nikolaidis, 2007). Temporary rivers respond to the annual variability of precipitation by producing first flush events of high intensity and infrequent erosional events difficult to study and anticipate (Gallart et al., 2008; Kirkby, 2005).

Sediment production, transport and deposition have an impact on water and nutrient circulation at a global scale. The world suspended sediment production is estimated to be 20×10^9 t y^{-1} of which over 25% is trapped in large dams constructed around the world (Takeuchi, 2004).

Quantification of sediment transport is important in order to characterize conditions and processes governing water quality, invertebrate and fish habitat, reservoir sedimentation and coastline dynamics (Bull and Kirkby, 2002; Vericat and Batalla, 2010; Syvitski et al., 2003). The most serious environmental impacts of sediment transport are manifested in lowland areas.

There is a limited number of sediment transport studies and field measurements in temporary rivers in Mediterranean region and this creates a significant gap in our understanding of soil erosion processes as well as the ecological and landscape impacts of sediment management (Rovira and Batalla, 2006). Models such as USLE (Wischmeier and Smith, 1965), SHETRAN (Bathurst et al., 1996, 2002, 2006), RUSLE (Renard et al., 1997), EUROSEM (Quinton, 1997) or WEPP (Flanagan et al., 2001) have been developed to estimate erosion rates at the field or catchment scale while global scale models such as Corine (Corine, 1992), Pesera (Kirkby et al., 2003), Medalus (Kirkby et al., 1998) have been used to estimate such rates at a continental scale. Erosion studies in Mediterranean countries underwent an important push during the last decade and a wide variety of empirical, conceptual or physically based models have been used (mostly in Spain and Italy) to understand erosion and sediment transport processes. On most of these studies the quantification of sediment loads is estimated either by using statistical techniques on past field measurements (sediment rating curves) or by creating erosion plots combining field water or sediment measurements (Vericat and Batalla, 2010; Rovira and Batalla, 2006; López-Tarazón et al., 2009; Rodríguez-Blanco et al., 2010; Nunes et al., 2011). Mean annual sediment yield can be also calculated from mathematical models calibrating and validating the total volume of sediment retained behind check dams with high siltation rates (De Vente et al., 2008; Bussi et al., 2014).

Few sediment transport studies have been conducted in Greece and these have been mostly for lakes and coastal environments. Valmis et al. (2005) developed a relationship using the instability index for estimation of soil interrill erosion rate. Hrissanthou et al. (2010) calculated the sediment inflow into Vistonis Lake by combining a physically based erosion model with a conceptual hydrological model and a stream sediment transport model while Kosmas et al. (2003) evaluated the effect of land parameters such as soil texture, soil depth, parent material, topography and climate on vegetation performance and degree of erosion for the island of Lesvos in Greece. Zarris et al. (2007) developed two equations in order to qualitatively describe the phenomena in terms of the relation between sediment yield and catchment geomorphology in eleven river catchments in Northwest Greece and compared these with earlier estimates published by other researchers. Panagopoulos et al. (2008) quantified soil losses and river sediment yields in Arachtos (Western Greece) catchment by implementing the SWAT model and regression relationships relating hydrometeorologic and/or geomorphologic catchment characteristics to sediment yields.

Sediment transport is one of the fundamentals processes that shape the physical environment. In the case of the Mediterranean countries, soil erosion has been identified as a major problem, resulting changes in soil characteristics, loss of productivity, reservoir calibration and changes on the quantity and quality of water resources. Quantification of sediment transport is important not only to understand river dynamics in general, but also to characterize and model associated fluvial features and processes such as fish and invertebrate habitat, stability of infrastructures, water quality, reservoir sedimentation and coastline dynamics. Predicting the spatial patterns and intensity of hydrology and sediment transport for large river basins can be problematic in areas where few reliable experimental data are available so other approaches that facilitate model simulations must be applied.

It is important to understand and quantify sediment loads in basins better despite the uncertainties of data scarcity arising from the technical difficulties of obtaining adequate and reliable suspended sediment data (López-Tarazón et al., 2009). Predicting spatial patterns and intensity of soil erosion and sediment transport can be problematic in areas where few reliable experimental data are available so other approaches must be applied.

The objective of this research was to study the spatial and temporal distribution of runoff and sediment transport of a large temporary river basin in Greece (Evrotas River Basin) by focusing on the collection of a variety of data to constrain modeling processes at various scales given existing budgetary limitations and the large area of the catchment. In particular, data such as river desiccation maps and sediment accumulation measurements in river reaches were systematically used to constrain the uncertainty in hydrology and sediment transport simulation of the basin.

In this work, the semi-distributed Soil and Water Assessment Tool (SWAT) model was used since SWAT model has shown to be an effective tool for assessing catchment management plans on hydrologic, sediment transport and water quality impacts on large watersheds (Nikolaidis et al., 2013; Oeurng et al., 2011; Betrie et al., 2011; Ndomba et al., 2008; Baffaut and Benson, 2009; Amatya et al., 2011).

2. Study area description

Evrotas River Basin has a drainage area of 1348 km^2 and is a complex hydrological system consisting of intermittent flow tributaries, high relief areas and springs which are the main contributors to base-flow (Fig. 1). It is located in the southeast part of Peloponnesus, Greece and drains into Laconikos Gulf. The Evrotas River develops from north to south, between the Taygetos and Parnonas mountains. The mountains of Taygetos and Parnonas, reaching a maximum elevation of 2404 m, affect Evrotas River hydrologic patterns. 65% of the basin area has slopes higher than 15%, 24% of the area ranges between 5–15%, and only 11% has slopes less than 5% depicting the rugged nature of the terrain. Its population density is 34 residents km^{-2}.

The Evrotas basin has a mild Mediterranean climate influenced by orography with wet winters (November to March) and long dry summers (April to October). Monthly mean temperatures are typically 4–11 °C in the winter and 22–29 °C in the summer (Tzoraki et al., 2011). The main activities in the catchment are agriculture, livestock and small agricultural industries. The land cover classes derived from Corine are scrub and/or herbaceous vegetation associations (60.8%), forests (16.0%), heterogeneous agricultural areas (15.0%), permanent crops (6.5%), open spaces with little or no vegetation (1.1%), urban fabric (0.3%), arable land (0.1%) and the rest (0.2%) are industrial, commercial and transport units, mine, dump and construction sites and artificial, non-agricultural vegetated areas. Many of Evrotas River tributaries and part of the main course become dry during the summer. The main tributaries are Inountas, Xerias, Magoulitsa, Gerakaris, Kakaris and Rasina. The main soil types that can be found on the watershed are Rendzina, Podzol and Alluvial Deposits.

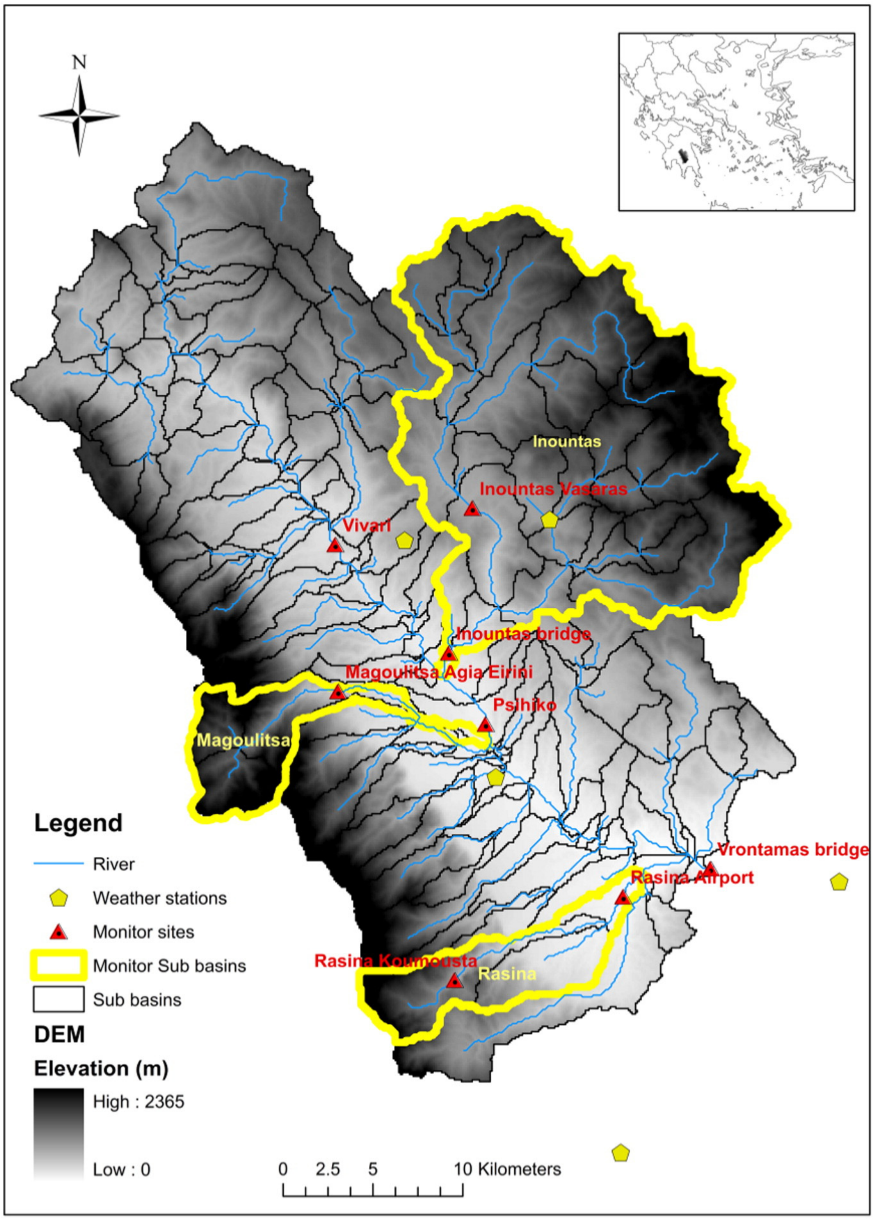

Fig. 1. Evrotas watershed.

The geological structure of the area includes almost all the geotectonic units of Peloponnesus (bottom to top: Plattenkalk or Mani Unit, Phyllite — Quartzite or Arna Unit, Tripolis Unit and Pindos Unit). The Plattenkalk Unit is the relatively autochthonous unit of the area of study. Generally, these units are stacked, in the sequence in which they were presented from the lower to the upper. In addition, various types of post-alpine formations appear in the study area. The most common types are Pliocene and Pleistocene sediments, including massive alluvial fans. These deposits cover the lower areas of the region, have great thickness and consist of clays, sands, pebbles, conglomerates, marls, sandstones in alterations. Furthermore, there are more recent, Holocene deposits, which are separated in alluvial deposits and scree. The geological structure described suggests that the area consists of many aquifers, which communicate hydraulically. The sequence of the nappes combined with the appearance of faults, creates a wide variety of hydrogeological conditions. The contact between the karstic rocks and the lower permeable and impermeable rocks regulates groundwater flow.

In general, there are three types of aquifers in the region: karstic aquifers, porous media aquifers, and hard rock fractured aquifers. Karstic aquifers are divided in three groups according to the geological unit to which they belong. In the post-alpine formations, water tables develop at several depths most of which communicate hydraulically with the karst aquifers or with Evrotas River. Finally, aquifers of smaller capacity are developed in the secondary porosity of hard rocks.

Current irrigation practices consume water at a rate twice the recommended, placing a major burden on water resources. In the Evrotas River Basin the water mass balance is positive and the needs for irrigation and drinking water are met. Problems are encountered during the summer due to increased irrigation demands (for example in 2007), which may result to the total dryness of Evrotas river network. In addition, numerous private wells that operate in Lakonia Prefecture have resulted to the lowering of the water table during dry periods. There are 150 public wells and approximately 3550 private wells which are located within the basin. Irrigation withdrawals were estimated to 62 mm^3 from groundwater wells and 15 mm^3 from direct abstractions from the stream.

3. Methods and materials

3.1. Experimental sampling design

The experimental sampling design of the hydrology and sediment transport of the watershed focuses on the collection of a variety of data to constrain processes at various scales, given the existing budgetary limitations and the large area of the watershed.

The Department of Environment and Hydrology, Region of Peloponnesus, Regional Unit of Lakonia has been monitoring the flow of Evrotas River from 1974 to 2006 in twelve locations along the main course of the River on a monthly basis. Since 2007 automatic level loggers have been used to measure water level on hourly basis in six of these areas. The data at Vrontamas station in the main corridor from 1974 were used for historical flow simulation. Historical simulations assume relatively constant land use in time. This is the case of Evrotas River Basin. The land use has not changed in the past 40 years. In addition, water level measurements from 14 irrigation wells measured two to five times per year were available since 1990.

In addition to establishing sampling stations to monitor the main corridor of the river, 3 subcatchments were instrumented from 2009 to 2011 to obtain detailed data for calibration of the different hydrotypologies of the catchment. Two of the subcatchments (Magoulitsa and Rasina) were draining Taygetos Mountain and one (Inountas or Kelefina) Parnonas Mountain. A total of 7 gauging stations (five in the subcatchments and two in the main corridor) were established to continuously monitor water level. Automatic level loggers (Onset Computers and HOBO pressure transducers U20-001-04) were installed to monitor water level every 10 min. These data were used to convert water level measurements to discharge using the rating curve (constructed from discharge values measured once every month) developed for every station. Rating curves relate water level to discharge based on the equation $Q = aH^b$, where Q is the discharge, H is the water depth and a and b are parameters based on the specific geometry of the studied reach.

Suspended sediments were monitored between February 2010 and May 2011 in the same 7 sites where flow was measured (two in the main corridor and five in the subcatchments). Additionally suspended sediments were monitored downstream the waste water treatment plant (Psihiko) in the main corridor. Grab samples of 1 L were collected once a month at each site to determine the suspended sediment concentration. The water samples were filtered in the laboratory using a pre-weighed filter. The residue retained on the filter was dried in an oven at 103 to 105 ° C until the weight of the filter no longer changed. The increase in weight of each filter represented the suspended sediment concentration for each water sample. The methodology was that of the EPA 160.2 Residue, Non-Filterable method (EPA, 1979).

River desiccation maps were used to calibrate the simulation of low flow. The term “river desiccation” is used to describe the extent of the river network that is drying out during the dry season. River desiccation is an important ecological parameter because it is related to the survival of fish and the ecological quality of the river (Skoulikidis et al., 2011). The flowing segments of the river were recorded on a map in April and until the end of the dry season in October of 2007 (Skoulikidis et al., 2011). These data were used to calibrate the model for low discharges by comparing the extent of the river network that was simulated as dry with the actual extent.

Suspended sediment concentrations of the Evrotas river during flood events were measured by Skoulikidis (2013) using an automated flood water quality ISCO sampler installed in Sentenikos gauging station, in the north-west part of the basin. ISCO portable automatic water sampler interfaced with a programmable datalogger/controller (CR205) was taking samples in short-term time intervals (every 10–15 min) in order to examine water quality variations during the first flood events. The autosampler was equipped with 24 bottles of 500 ml.

Flow and suspended sediment duration curves for each reach were constructed from daily discharge data (Gamvroudis et al., 2011). In addition, two river reaches (Magoulitsa at Agia Irini and Rasina) were topographically surveyed annually (total of three field surveys) during 2009–2011. The surveyed area in each reach was divided in 10 cross sections with steady points and sufficient space between them in order to measure volume changes. The stream surface area surveyed at Magoulitsa was 1000 m^2 and at Rasina 2500 m^2. Cross section data were contoured using the Surfer contouring software and a three-dimensional representation of each reach was created and the changes of bed volume were estimated. In order to find the accumulated mass the calculated volume was multiplied by the density (~1200 kg m^{-3}) of the soil. To estimate the simulated sediment yield in the same segments as the cross-section surveyed the SWAT model was run for the same time intervals as the surveys. The differentiation on sediment yield between the starting and ending period of simulation provided the net erosion or net deposition for each specific period and segment. Knowing the length, width and area of each segment the specific erosion/deposition was calculated for a single hectare and compared it with the respectively cross section estimations.

3.2. Model set-up and simulation

The Soil and Water Assessment Tool (SWAT) is a process-based model that simulates continuous time landscape processes at a catchment scale. The catchment is divided into Hydrological Response Units (HRUs) based on soil type, land use and slope classes. Model components include hydrology, weather, soil erosion, nutrients, soil temperature, crop growth, pesticides agricultural management and stream routing (Arnold et al., 1998; Neitsch et al., 2005a,b).

The model divides watersheds into subwatersheds and further into hydrologic response units (HRUs) based on land use, soil, and slope information. The model requires several parameters to simulate hydrologic and water quality processes. These include weather, soils, ground water, channel, plant water use, plant growth, soil chemistry, and water quality parameters, as well as sub-basin and HRU characterization data. The SWAT model contains built-in climate, soils, and plant growth databases that can be used as data sources for climate, soil, and plant growth parameters. The basic parameters, however, are those pertaining to land use, soil, topography and climate (Gitau and Chaubey, 2010).

The ArcGIS interface of the SWAT2009 version was used to spatially discretize the study catchment. For the model calibration and validation monthly and daily river discharge data and monthly suspended sediment concentration data were used. The STRM 90 m resolution data were used to develop the Digital Elevation Model (DEM). The land use types of the study area were extracted from the Corine Land Cover 2000 (CLC2000) which is produced by the European Environment Agency (EEA, 2007) and its member countries in the European Environment Information and Observation Network (Eionet) and has a 25 ha spatial resolution which is based on the results of IMAGE2000, a satellite imaging program undertaken by the Joint Research Centre of the European Commission and the EEA. The soil categories were derived from the European Soil Database and contain attributes from the Soil Geographical Database of Eurasia at scale 1:1.000.000 (v4.0 beta) and the PedoTransfer Rules Database (v2.0). The soil types of the study area were extracted from the SOIL-FAO database, Food and Agriculture Organization of the United Nations (FAO, 1995). Five precipitation stations and three temperature stations located within the basin were used to drive the hydrologic model using daily data. These stations have been in operation since 1970 and are the following: Riviotissa (163.5 m), Vrontamas (280 m, operating since 1953), Perivolia (490 m), Sellasia (590 m) and Vasaras (646 m) (Fig. 1). In addition, there is the Ellos (4 m elevation) daily precipitation station and five more precipitations stations (Arna, Kastori, Petrina, Sparta and Karyes) with monthly precipitation records. All these stations were used to

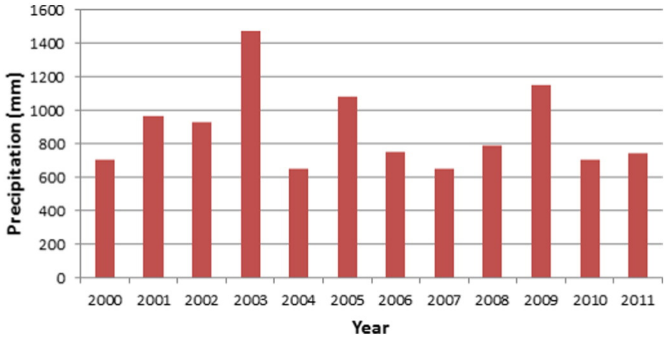

Fig. 2. Annual precipitation of Evrotas watershed (2000–2011).

Table 1
SWAT sediment transport parameters, their range and the calibrated values.

Rank	Name	Description	SWAT range	Evrotas
1	SOL_AWC	Available water capacity in soil layer	0.0–1.0	0.22–0.85
2	GWQMN	Threshold water depth in the shallow aquifer for flow (mm H_2O)	0–5000	100–5000
3	GW_REVAP	Groundwater “revap” coefficient	0.02–0.2	0.02–0.2
4	ESCO	Soil evaporation compensation factor	0.01–1.0	0.6–0.8
5	ALPHA_BF	Baseflow alpha factor	0.0–1.0	0.005–0.9
6	CN2	SCS runoff curve number	35–98	35–60
7	GW_DELAY	Groundwater delay	0–500	1.0–50
8	RCHRG_DP	Deep aquifer percolation coefficient	0.0–1.0	0.0–1.0

develop the precipitation lapse rates for Parnonas and Taygetos mountains. Missing precipitation data were estimated using linear regression methods (Maidment, 1993). Fig. 2 presents the annual precipitation (mm) of Evrotas watershed during the period 2000–2011. The basin was delineated into 150 sub-basins which are further subdivided into homogeneous hydrologic response units HRUs. The amount of irrigation that was used in SWAT was estimated from the agricultural usage of electricity and the direct withdrawal from the river for irrigation purposes (Tzoraki et al., 2011). Irrigation withdrawals were estimated to be 77 Mm^3 from groundwater wells and direct abstractions from the stream. We estimated that current irrigation practices consume water at a rate twice the recommended, placing a burden on water resources. Irrigation is included in the model as an auto-application of irrigation in each HRU in response to a water deficit in the soil needed for plants to grow.

The model was calibrated with the observed runoff for the years 2009–2011 for all stations and validated for the years 2004–2009 for the Vrontamas and Vivari gauging stations. The model was calibrated with suspended sediment concentration data for the years 2010–2011. A sensitivity analysis was used as a tool for reducing the number of parameters to be adjusted during calibration. The sensitivity analysis was carried out by the sensitivity analysis tool of ArcSWAT (Veith and Ghebremichael, 2009). Sensitivity is expressed by a dimensionless index (sensitivity index) which is calculated as the ratio between the relative change of model output and the relative change of a parameter.

The percent bias (PBIAS), the Nash–Sutcliffe efficiency (NSE), and the ratio of the root mean square error to the standard deviation of measured data (RSR) were used as evaluation methods to assess model performance and goodness of fit as suggested by Moriasi et al. (2007).

The Nash–Sutcliffe efficiency (NSE) is computed as the ratio of residual variance to measured data variances (Nash and Sutcliffe, 1970). The percent bias (PBIAS) measures the average tendency of the simulated data to be larger or smaller than their observed counterparts (Gupta et al., 1999). The ratio of root mean square error to the standard deviation of measured data (RSR) is calculated as the ratio of the root mean square error (RMSE) and standard deviation of the observed data (Moriasi et al., 2007). According to Moriasi et al. (2007) model simulation is judged as satisfactory if $NSE > 0.5$, $RSR < 0.70$ and $PBIAS = \pm 25\%$ for flow and $NSE > 0.5$, $RSR < 0.70$ and $PBIAS = \pm 55\%$ for sediment.

4. Results and discussion

4.1. Hydrological assessment

The model was calibrated with the observed runoff for the years 2009–2011 for all stations and validated for the years 2004–2009 for Vrontamas and Vivari gauging stations. For the calibration, one year was used as a warm-up period of the model.

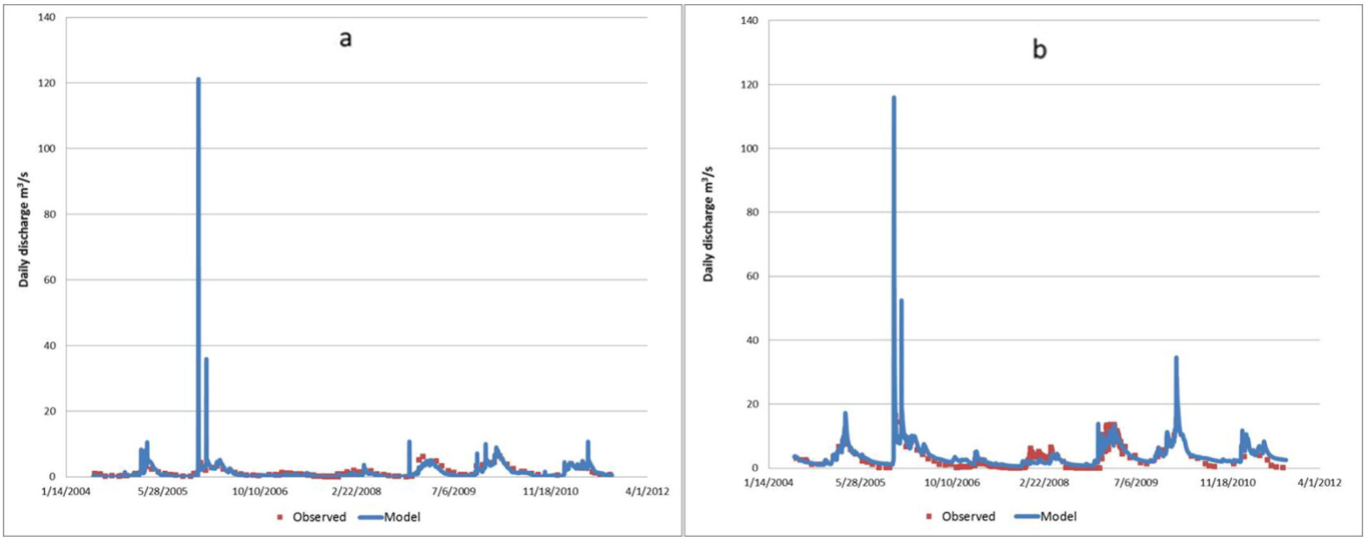

Fig. 3. SWAT simulated and observed discharge for a) Vrontamas and b) Vivari gauging stations.

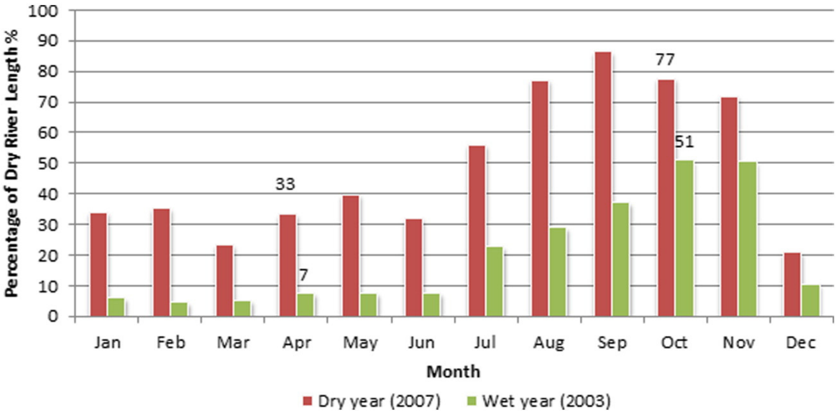

Fig. 4. Evrotas simulated river desiccation evolution of 2007.

Fig. 3 presents the comparison of simulated daily discharges versus observed data for Vrontamas (a) and Vivari (b) main gauging stations respectively for both the calibration (2009–2011) and verification periods (2004–2009).

The fit between the model discharge predictions and the observed discharge showed good agreement as indicated the evaluation of the NSE, RSR and PBIAS indices. The NSE, RSR and PBIAS values of the discharge for the calibration period were 0.80, 0.45, and −11.4%, for Vrontamas station and 0.59, 0.64 and 17.0% for Vivari station respectively. The coefficient of determination R^2 was 0.716 and 0.678 for the two stations respectively. These values were within the acceptable levels reported in the literature. Similarly, the NSE, RSR and PBIAS values for the validation period were respectively 0.80, 0.45, and −18.9%, for Vrontamas station and 0.54, 0.68 and 23.6% for Vivari station respectively. The main calibrated parameters, their range and the calibrated values are summarized in Table 1.

An average hydrologic budget was constructed using a 12 year long (2000–2011) simulation of the catchment. The average precipitation of the basin for this period was estimated to be 903 mm yr^{-1}. The actual evapotranspiration was 46.9% (424 mm yr^{-1}), and the total water yield was 13.4% (121 mm yr^{-1}). The remaining 33.4% (302 mm yr^{-1}) was the amount of water that was lost through the deep groundwater of Taygetos and Parnonas Mountains to areas outside the watershed and for drinking water demands (6.3%).

Andreadakis et al. (2008) have identified the Eastern part of the region (Parnonas Mountain) as an area that suffers from water shortage

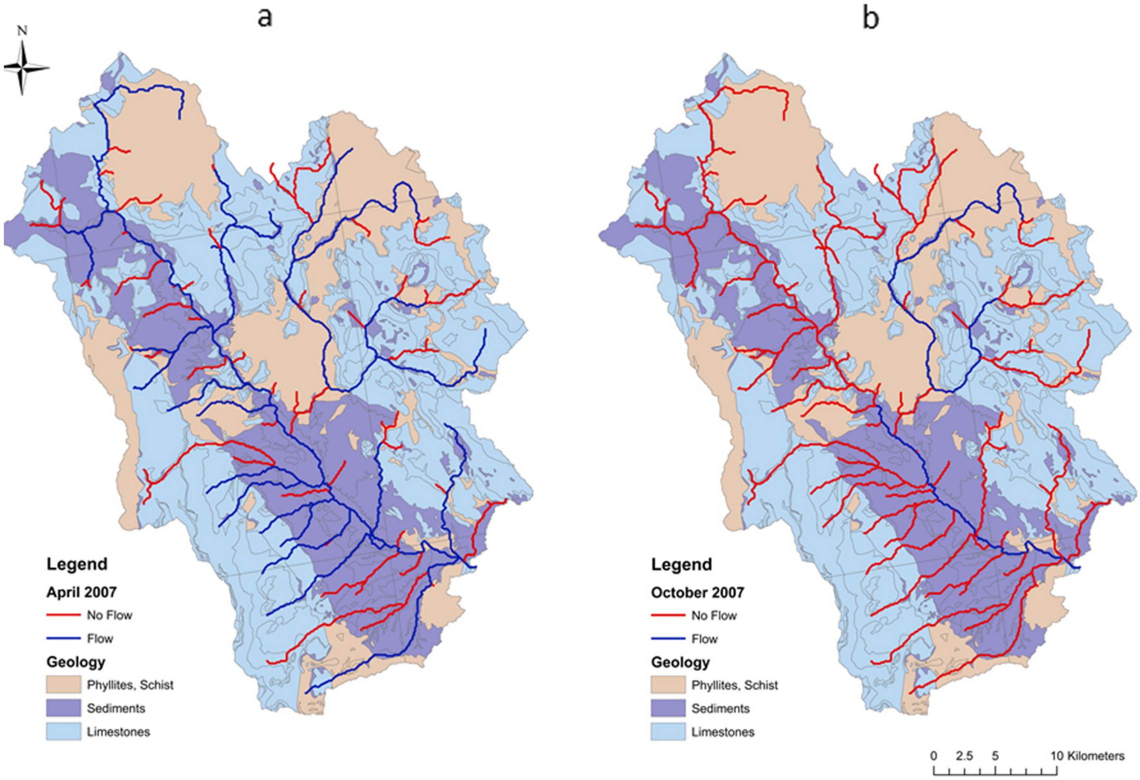

Fig. 5. Hydrological simulated map of Evrotas catchment in a) April and b) October of 2007.

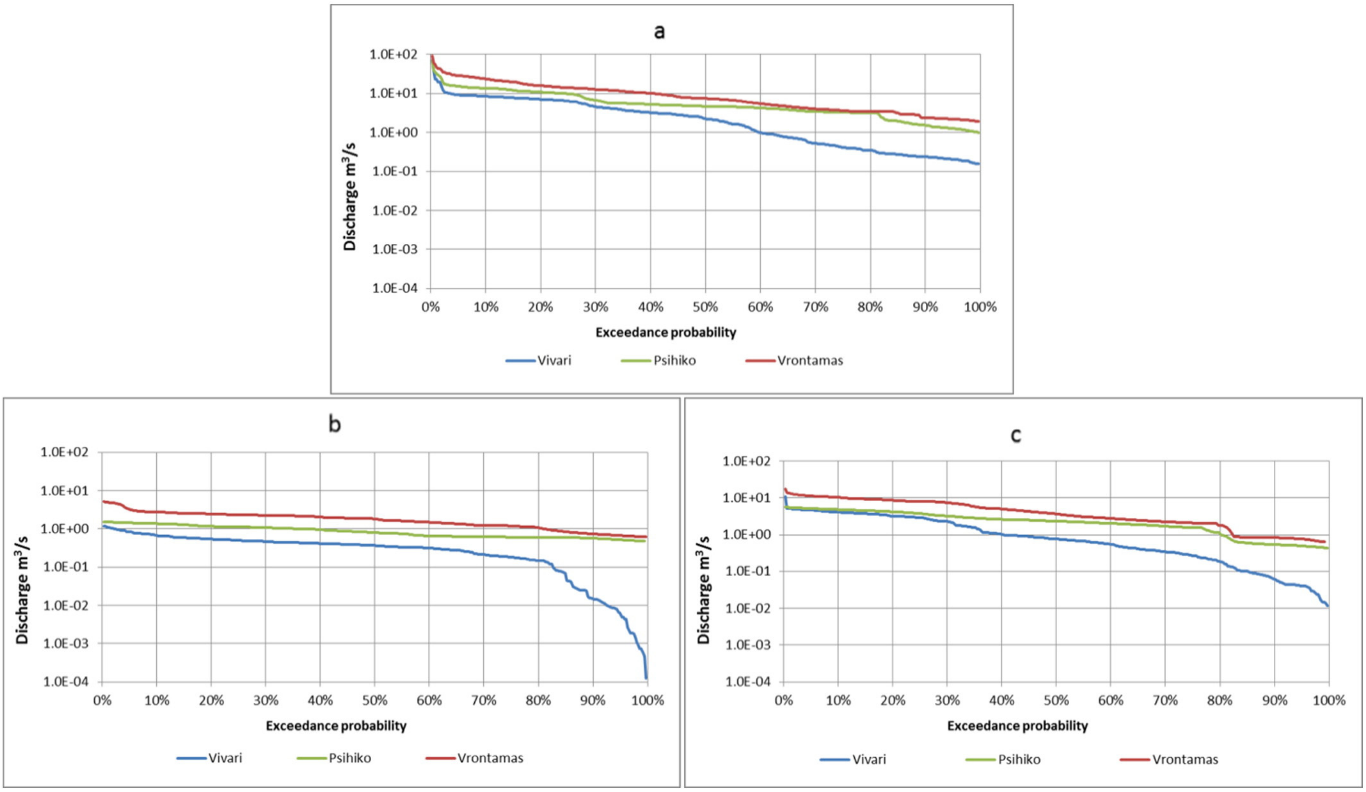

Fig. 6. Simulated flow duration curves of the main river of Evrotas in a) wet (2002–2003) b) dry (2006–2007) and c) typical (2008–2009) year.

caused by its geology. The karst formations drive groundwater to great depths (almost down to sea level), and then to the East (Myrtoon sea). On the other hand at the North and Northwest part of the region (Taygetos Western margin) water resources are more abundant, due to a number of important spring outlets draining the karstic aquifers. Aquaclude formations isolate some of the limestone tectonic nappes and at the same time force leakage towards the interior of the basin. Moreover, the alluvial fans host porous aquifers fed by the adjacent karstic ones.

The variability of rainfall during this period was significant ranging from 1474 mm in 2003 (wet year) to 647 mm in 2007 (dry year). In general, rainfall in the region occurs mostly during the autumn–winter (70%) and only 20% in the spring. The highest 24 h rainfall intensity occurred on 24/11/2005 and was 129 mm while 75% of the rainfall events had intensity below 10 mm.

The results of the 1970–2010 SWAT simulation suggested that there has been a significant reduction in flow after the drought of 1989, indicating a climatic shift in the hydrologic regime of the area. The average water yield of the period 1970–1988 has been reduced from 277.1 mm (21.2% of precipitation) to 134.8 mm (15.2% of precipitation) in the period 1989–2011 as a result of the reduction on the precipitation from 1304.4 mm to 884.1 mm in the same period. The NSE, RSR and PBIAS values of the flow for the 1974–2011 period were 0.53, 0.69, and −23.0%. Results are considered good for NSE and RSR and satisfactory for PBIAS.

In general, almost 90% of Evrotas river network length is comprised of episodic river segments and only 10% is comprised of perennial and intermittent river segments. Fig. 4 presents the evolution of the simulated river desiccation (% of river length dry) in 2003 (wet year) and 2007 (dry year). During April and October of 2003 the dry river segments increased from 7% to 51% while during April and October of 2007 from 33% to 77%.

To further constrain the range of the parameters of the hydrologic model during low flows, river desiccation maps were created by identifying the flowing river segments and the dried out segments for the whole river network at different periods. To evaluate the hydrologic simulation of SWAT for the basin during the dry period, we used river desiccation maps of the watershed developed by Skoulikidis et al. (2011) for the drought year of 2007 and compared them with similar maps developed through model simulations. Fig. 5 presents two snapshots of the simulated river network (April and October 2007) in order to illustrate the evolution of desiccation during a drought year.

These results are comparable with the actual river desiccation maps developed by Skoulikidis et al. (2011) for the same time period, providing additional evidence that the model can consistently depict low flow conditions in the basin. Skoulikidis et al. (2011) conducted a survey were the dry and wet segments of the River network were recorded several times during a dry year (2007). This was done during field visits along the river network length and represents a static situation of river desiccation. In temporary rivers during artificial desiccation environmental changes occur causing rapid and extensive deterioration of water quality and habitats, and organisms may face conditions which they have not experienced in their recent evolutionary history. We examined the river condition as simulated by SWAT on a subbasin level and corresponded the river segments described by Skoulikidis with those of SWAT. Monthly average discharge values were estimated in April and October of 2007, representing the beginning and the end of the dry period in Evrotas and a cut-off value of 0.01 m^3/s was chosen to show no flow conditions on the SWAT discharge estimations. Based

Table 2
SWAT sediment transport parameters, their range and the calibrated values.

Rank	Name	Description	SWAT Range	Evrotas
1	Spcon	Coefficient in sediment transport equation	0.0001–0.01	0.00025
2	Spexp	Exponent in sediment transport equation	1.0–1.5	1.5
3	Ch_N2	Manning's n value for main channel	−0.01–0.3	0.14
4	Usle_P	USLE equation support practice factor	0.0–1.0	0.9
5	Ch_Cov	Channel cover factor	−0.001–1.0	0.0

Table 3
Comparison between SWAT estimated and measured sediment accumulation.

		Channel deposition (tons)		
Reach	Period	Cross Sections	SWAT	Error %
Rasina	March 2009–March 2010	80.7	60.6	−24.9
	March 2010–July 2011	72.4	73.3	1.2
Magoulitsa	March 2009–March 2010	7.8	4.1	−47.4
	March 2010–July 2011	23.1	27.6	19.4

on this comparison, the flowing segments of the two maps were compared. More than 85% of the river segments represent same flow characteristics with the actual river desiccation maps providing additional evidence that the model can consistently depict low flow conditions in the basin.

The spatial distribution of water yield is reflecting the hydromorphologic conditions of the basin where most of the yield is generated by the Taygetos mountain karstic system. The water yield for the whole catchment ranged from 272.9 mm (17.0% of precipitation) in 2002–2003 to 47.9 mm (7.9% of precipitation) in 2006–2007 with a typical value of 158.3 mm (16.8% of precipitation) in 2008–2009. The variability of the water yield of Evrotas River during a wet (2002–2003) and a dry (2006–2007) year was a combined effect of rainfall and water abstraction variability in these years.

Fig. 6 presents the flow-duration curves in a wet (2002–2003), dry (2006–2007) and typical (2008–2009) year at three gauging stations (Vivari, after the waste water treatment plant (Psihiko) and Vrontamas) in the main corridor of Evrotas River. Kirkby et al. (2011) suggested that differences in monthly flow duration curves can be used to classify the characteristic signatures of climate and the contrasting hydrological regimes that are driven by climatic differences. The three stations maintain the same characteristic flow distribution order (less steep from North to South). The flow duration curves of the Eastern tributaries are more typical of episodic streams while the Western tributaries of flush streams.

The shape of the flow duration curves of the main corridor can identify both the extreme flows as well as the transition from perennial to ephemeral state. The exceedance percentage of 3% can be used as a threshold for flood conditions based on the point of the duration curves for the wet year 2002–2003. The point that defines the dry state can only be defined for the Vivari station corresponds to the exceedance percentage of 80%. The results suggest that Vivari reach can dry out up to 20% of the time depending on climatic conditions. Tzoraki et al. (2013) suggested that the seasonality pattern of flush floods in Evrotas are in agreement with other studies in Greece and differs from other European floods. The frequency of flush floods in the main corridor of the river is estimated to be between 5% and 7% of the total floods.

Sensitivity analysis results indicated that the most sensitive parameter of hydrological parameters was the available water capacity (Sol_Awc). A second group of parameters with similar significance was the threshold water depth in the shallow aquifer (Gwqmn), the groundwater evaporation coefficient (Gw_Revap), the temperature lapse rate (Tlaps), the channel effective hydraulic conductivity (Cn_K2) and the soil evaporation compensation factor (Esco). Other parameters such as the baseflow alpha factor (Alpha_Bf), the soil depth (Soil_Z), the saturated hydraulic conductivity (Soil_K), the SCS runoff curve number (Cn2) and the average slope steepness (Slope) were identified as slightly important. The important parameters indicate

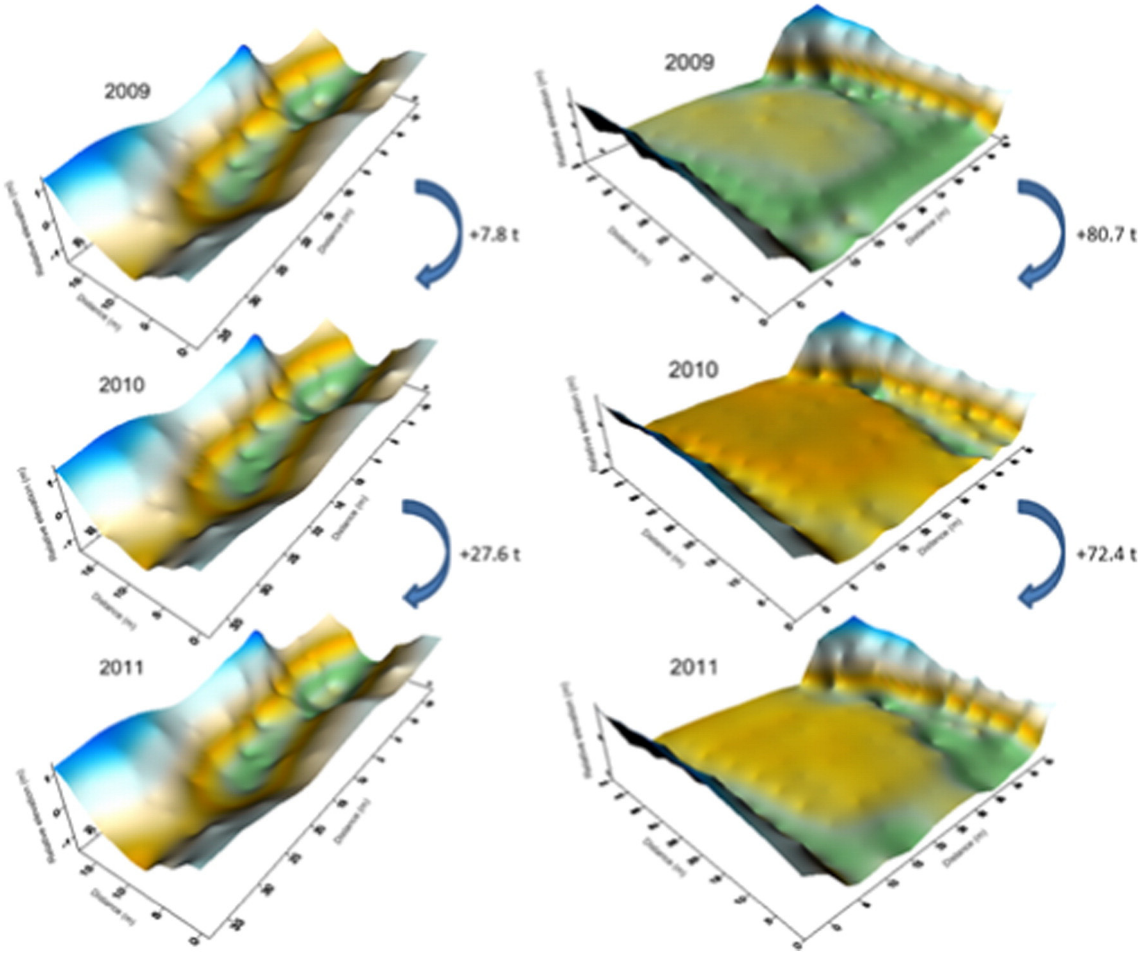

Fig. 7. 3-D cross section image of Magoulitsa and Rasina reach.

that the water flow in this region is dominated by infiltration, percolation and baseflow due to shallow groundwater. The identified sensitive parameters in this study are consistent with those identified in the scientific literature (Ndomba et al., 2008; Schmalz and Fohrer, 2009; Betrie et al., 2011; Schuol and Abbaspour, 2006; Mukundan et al., 2010). Deogratias et al. (2007) showed that the SCS runoff curve number (CN2) and the saturated hydraulic conductivity (SOL_K) parameters were the most sensitive parameters modeling the Simiyu River.

4.2. Sediment yield assessment

The model was calibrated using suspended sediment values measured once per month during 2010–2011 in 8 stations. Table 2 shows the acceptable range of SWAT parameters and their chosen values for the current study.

The coefficient parameter and the exponent parameter in SWAT sediment transport equation determine the maximum concentration of sediment that can be transported. The coefficient value was set equal to 0.00025 and the exponent 1.5. The support practice factor of the USLE equation is defined as the ratio of soil loss with a specific support practice factor to the corresponding loss with up-and-down slope (Neitsch et al., 2005a) and it was set equal to 0.9. The simulation was considered acceptable based the statistics obtained between simulated and observed data for the calibration period with NSE, RSR and PBIAS equal to 0.77, 0.48, and 33.4% for Vrontamas station at the exit of the catchment and 0.75, 0.50 and 13.4% for Vivari station respectively. The coefficient of determination R^2 was 0.994 and 0.899 for the two stations respectively. Although the fit between the model and the observed concentrations showed good agreement, the drawback of the sampling was the lack of data during flood conditions. The maximum suspended sediment concentration measured by Skoulikidis (2013) in the river during the flood event of 25/01/2011 was 6000 mg L^{-1} and the flood event of 28/01/2011 2400 mg L^{-1}. SWAT simulated suspended sediment concentrations for both events were 5683 mg L^{-1} during the first event and 1841 mg L^{-1} during the second event. These values compare well with the measured data suggesting that SWAT has the potential of simulating high discharges appropriately. Additional high flow measurements should be collected in the future in order to reduce the uncertainty in the predictions of sediment fluxes.

The three-dimensional representation of each topographically surveyed reach (Magoulitsa at Ag. Irini and Rasina) indicates that there was an increase on the bed volume of both reaches during March 2009 and July 2011 suggesting sediment deposition. There was a total accumulation of sediments of 153.1 t for Rasina and 30.9 t for Magoulitsa over a two year period. The accumulated sediment mass was simulated with SWAT and the results are presented in Table 3 in comparison with the sediment channel deposition estimates at the cross sections.

The three-dimensional representation of each topographically surveyed reach (Magoulitsa at Ag. Irini and Rasina) is presented in Fig. 7. SWAT estimated a total accumulation of sediments of 133.9 t for Rasina and 31.7 t for Magoulitsa over a two year period which corresponds to an overall error of 12.5% and 2.6% respectively. These results suggest that the model provided satisfactory sediment simulations.

Fig. 8 presents the average annual sediment yield of each sub-basin for 2000–2011. The average sediment simulated yield for the whole watershed was 0.85 t ha^{-1} yr^{-1}. The highest annual sediment yield was generated in the western part of the catchment (3.5 t ha^{-1} yr^{-1}) didn't exceed the estimated tolerance limits (2 and 12 t ha^{-1} yr^{-1}) for Mediterranean environments established by López-Bermúdez et al. (1998). There is a big variability in the sediment yield values within the catchment.

The temporal and spatial distribution of simulated sediment yield in Evrotas for a wet (2003–2004), dry (2006–2007) and typical (2008–2009) year is presented in Fig. 9. The majority of the simulated sediment yield was generated during two storms in January 2003 and November 2005. Specifically, the simulated sediment yield for the January 2003 storm was 92,750 t at Vrontamas area in the exit of the catchment. Maximum values of sediment concentration appeared in 2003 (6356 mg l^{-1}) and 2008 (3021 mg l^{-1}) while minimum values appeared in 2007 (drought year). Reductions in simulated sediment yields also occurred as a result of reductions in river discharge due to water abstractions. The flow reduction contributes, by accelerated sediment deposition, to the raising of riverbed elevations and the increase in flood risk. Soils in Evrotas exhibit high susceptibility to water erosion due to their loamy-sand texture. Sub-basins with high rates of simulated sediment yield have steep slopes and are located mostly on the upper parts of Taygetos and Parnonas mountains.

The suspended sediment-probability relationship in the main River of Evrotas is presented as a log-normal plot in Fig. 10 The shapes of the sediment probability curves were different between mainstream and tributaries reflecting the geomorphological aspects of the channel and the surrounding soil erodibility. A characteristic point in the curve is the inflection point that separates the high flow sediment concentration to normal flow. High sediment concentrations exceeded <15% of the time during a wet year, <10% of the time during a typical year and <5% of the time during a dry year. The Vivari station had a high concentration inflection point and then was relatively flat indicating continuous low flow conditions while the downstream had two inflection points, one for the floods and another for the drying out of the flow.

Sediment parameters sensitivity analysis indicated that the most important parameters were the coefficient of the sediment transport equation (Spcon), the baseflow alpha factor (Alpha_Bf), the temperature lapse rate (Tlaps), the exponent in sediment transport equation (Spexp), the Manning's n value for main channel (Ch_N2), and the USLE support practice factor (Usle_P). The results were less sensitive

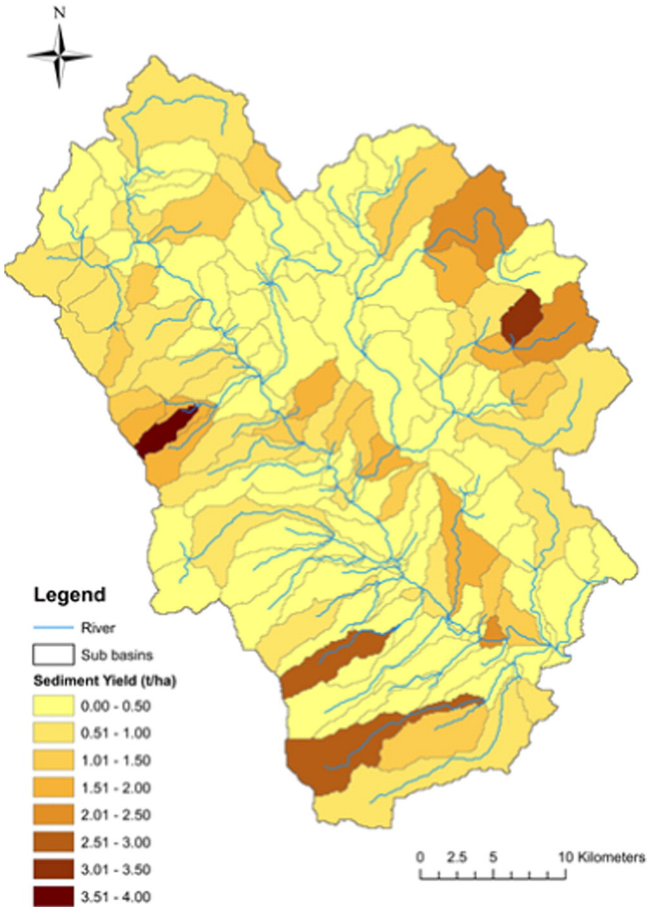

Fig. 8. Mean annual sediment yield from each sub-basin (2000–2011).

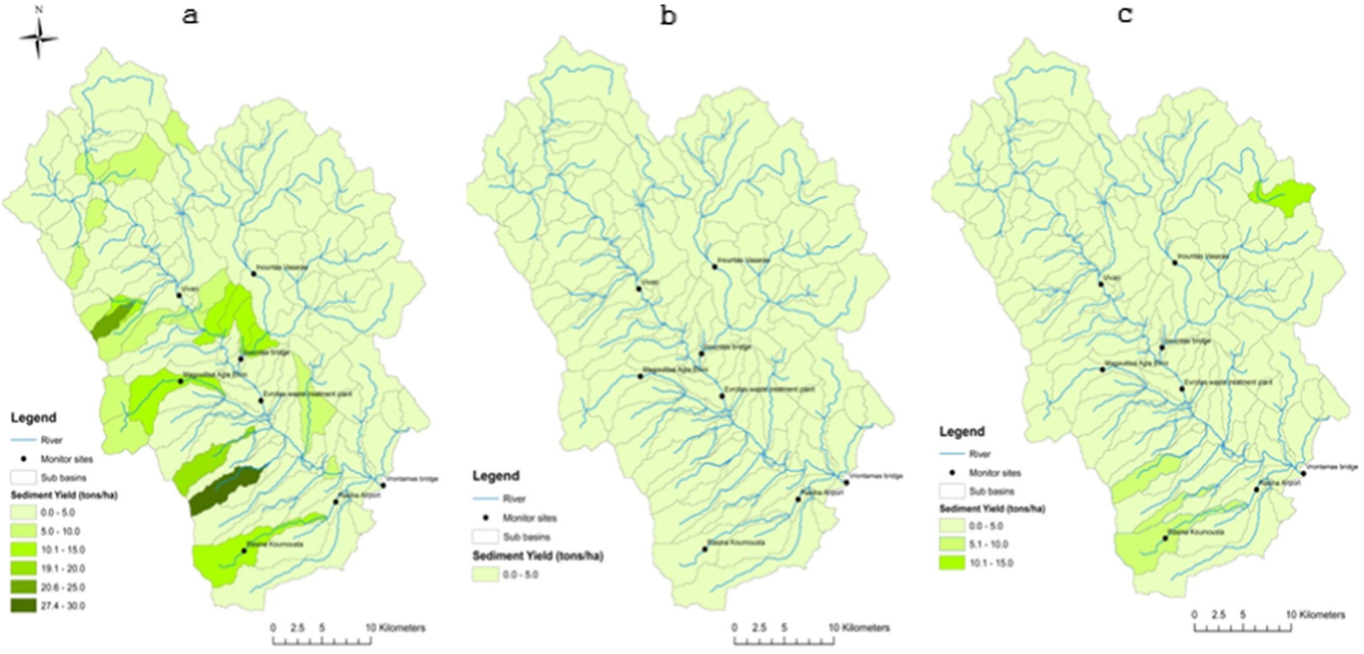

Fig. 9. Spatial distribution of sediment yield in Evrotas in a) wet (2002–2003) b) dry (2006–2007) and c) typical (2008–2009) year.

to parameters like the soil evaporation (Esco), the channel effective hydraulic conductivity (Ch_K2), the threshold water depth in the shallow aquifer (Gwqmn) and the SCS runoff curve number (Cn2). Studies by Mukundan et al. (2010), Oeurng et al. (2011) and Betrie et al. (2011) also pointed out the coefficient in the sediment transport equation (Spcon) and the exponent in the sediment transport equation (Spexp) as the most important sediment calibration parameters determining the maximum concentration of sediment that can be transported.

5. Conclusions

Predicting the spatial patterns and intensity of hydrology and sediment transport for large river basins can be problematic in areas where few reliable experimental data are available so other approaches that facilitate model simulations must be applied. A study of the spatial distribution of runoff and sediment transport of a large temporary flow river basin in Greece was conducted using the SWAT model and

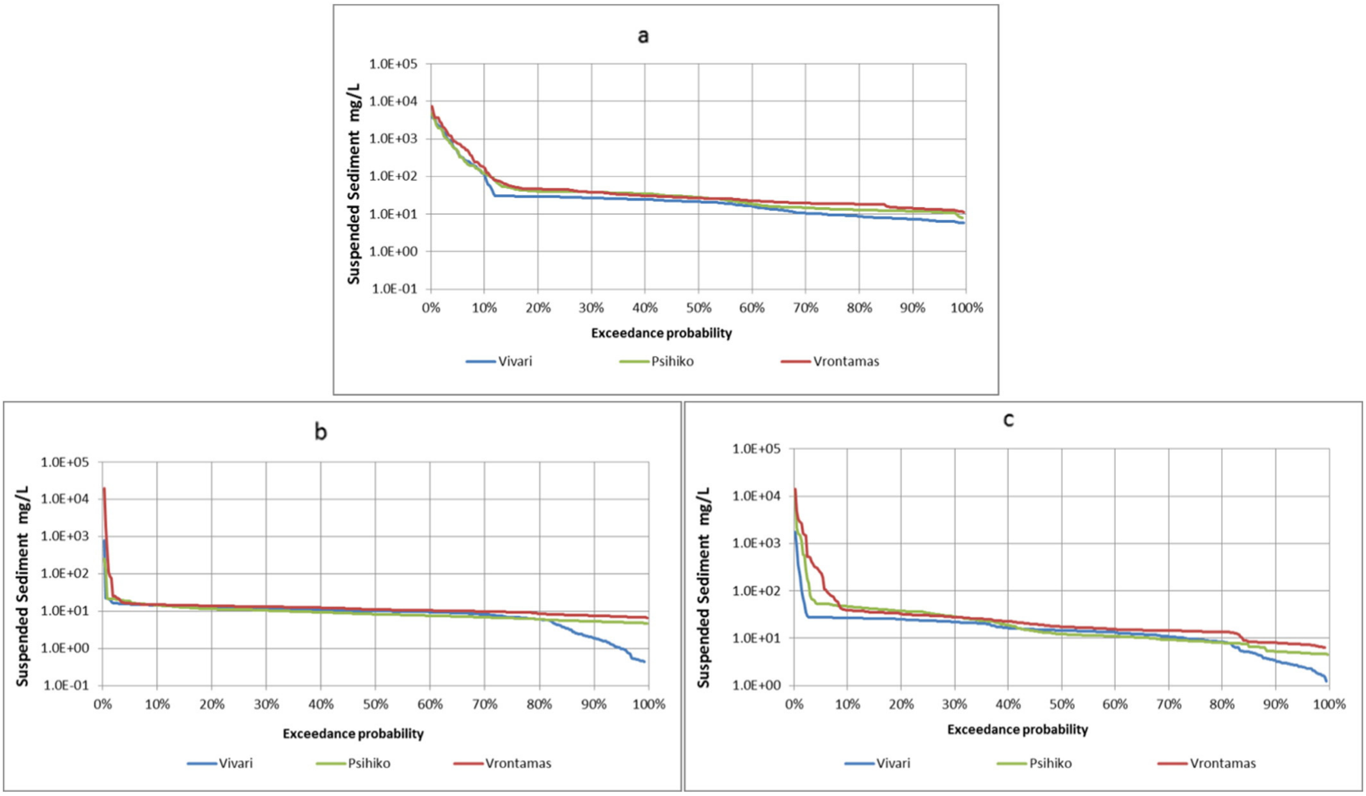

Fig. 10. Suspended sediment duration curve of the main river of Evrotas in a) wet (2002–2003) b) dry (2006–2007) and c) typical (2008–2009) year.

focusing on the collection of a variety of data to constrain processes at various scales, given existing budgetary limitations and the large area of the catchment.

Hydrologic and sediment transport data were collected at the site on a regular basis. In addition, annual measurements of sediment accumulation in two reaches were used to further constrain the sediment simulation. Finally river desiccation maps were used to constrain the hydrologic simulation, identify the response of the basin to drought events and better assess the ecological quality of the river.

Model simulation of hydrology and sediment transport was in good agreement with field observations. A 12 year long (2000–2011) average hydrologic budget was constructed using the simulation results of the catchment. The average precipitation was 903 mm yr^{-1}, the actual evapotranspiration 424 mm yr^{-1}, and the total water yield 121 mm yr^{-1}. The remaining 302 mm yr^{-1} was lost through the deep groundwater of Taygetos and Parnonas Mountains to areas outside the watershed and for drinking water demands. On the average the catchment has water surplus to cover water needs, however, during the dry years, the majority of the reaches dried out and water demand is covered from groundwater abstractions. The important parameters indicate that the water flow in this region is dominated by infiltration, percolation and baseflow due to shallow groundwater. The average sediment yield was 0.85 t ha^{-1} yr^{-1} exhibiting a large variability within the catchment (highest yield of 3.5 t ha^{-1} yr^{-1}). Hotspots of soil erosion were identified in the south-western part of the catchment.

The developed methodology constrained the parameters of the hydrologic and sediment transport simulation of the catchment providing consistent results and suggesting its usefulness as a tool for temporary rivers management.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2014.12.005.

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