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Impacts of Human Interaction on the Sediment Transport Processes in the Arachtos River Basin, Western Greece

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Abstract: Great efforts are needed nowadays in order to protect coastal areas from erosion in the Eastern Mediterranean as well as to develop general national and international standards for the assessment of the "state of the coast", its evolution and the causes of such evolution. The problem of erosion is dramatic in several coastal areas of Western Greece and, specifically, in the regions where anthropogenic interventions took place during the last 30 years. The Arachtos river basin in Epirus, where severe storms cause significant runoff and soil losses, is a very representative area, where sediment transport processes have been disturbed due to extensive human activities. Since 1981, when a dam operation begun along the river, approximately 20 km upstream of the watershed outlet, sedimentation rates at the estuary have been dramatically changed. High amounts of sediment material, transported with river flow, have been deposited in the reservoir and have rapidly decreased its dead storage capacity, while the reduction of sediment deposition at the outlet has caused considerable changes to the morphology of the estuary. The purpose of this paper is to implement scientific methodologies in order to fully represent and accurately quantify the consequences of the aforementioned human intervention in the Arachtos river basin as well as to propose solutions of the problem in terms of examining the effects of realistic and low-cost mitigation measures. The physically-based SWAT (Soil and Water Assessment Tool) model was firstly implemented for the integrated modelling of the Arachtos river basin. The hydrological and erosion regimes of the catchment were accurately simulated, while the reservoir impact on the river sediment yields was also adequately quantified. The application of different series of regression formulae that relate catchment hydrometeorological and geomorphologic characteristics to sediment discharge in selected river sites was then followed in order to check the SWAT results, whereas a clear estimation of the dam's trap efficiency was carried out as well. Finally, pre-specified land use change scenarios, including the application of crop rotations and special cultivation techniques on parts of the agricultural land of the catchment, were implemented with the use of the SWAT model in order to examine possible reduction in soil losses and sediment transport to the reservoir. The entire work revealed the significant soil susceptibility of the catchment that led to an average sedimentation rate of 3.7 Mtn/y at the outlet under natural conditions. After the dam construction, this significant rate was dramatically reduced to 0.085 Mtn/y with the dam's trap efficiency being nearly 98%. However, all land use change scenarios implemented with the SWAT model, resulted in a decrease in soil losses and sediment yields in the reservoir comparing to the current state. The cultivation of crop rotations under specific support practices can be efficient low-cost measures against erosion contributing up to a 20% prolongation of the reservoir life. On the other hand, the hard policy of the dam "opening" seems to be the only effort for the beach "nourishment" with sediments and consequently for the rehabilitation of the natural land-sea interactions in the coastal zone that have been significantly disturbed due to the dramatic increase of the erosive ability of water released from the dam.

Keywords: coast, erosion, human intervention, land use change scenarios, reservoir, sedimentation rates, sediment yields, soil losses, SWAT.

1. INTRODUCTION

The necessity of dealing with the problem of protecting the coastal areas from erosion arises rapidly all around the world and especially in the Mediterranean. General standards for the assessment of the 'state of the coast', its evolution and the causes of such evolution are at least needed at national level. A particular effort is currently devoted to fulfilling the recommendations of European Parliament and Council concerning the implementation of Integrated Coastal Zone Management in Europe (2002/413/EC). Human activities, sea level-rise as well as climate change are some of the most important factors of land degradation. Deltas pose a set of more specific problems as they are the areas where sea and land most closely interact.

Findings arising by catchment experiments provide clear evidence of the strong relation of erosion rates, land use and human activities (Walling, 1999). Interventions along rivers, such as dams, clearly affect the balance of materials exchanged between the land and the sea that are considered to be a dynamic equilibrium. Changes of the flow and sediment discharges can become influential in the evolution history of the coast (Bonora et al., 2000) as well as the trapping of sediments in the reservoirs can rapidly decrease their dead storage capacity. This currently happens in the Arachtos river basin in Western Greece, where the sedimentation patterns of the downstream part of the catchment have been significantly changed, mainly due to dam construction along the river, approximately 20 km upstream of the watershed outlet. Since 1981, when the Pournari I dam became operational, the reduction in sediment supply caused erosion in the coastal areas, mainly adjacent to river mouths, while in the following years the erosion phenomena became more widespread and involved progressively larger coastal segments with the lowest part of the river mouth being significantly retreated (Kapsimalis et al., 2002). By means of a digital terrain model of the Arachtos delta, recently prepared by applying photogrammetry and GIS techniques, the images of the area in the years 1960, 1985 and 1996 have been also compared (Figure 1), documenting the rapidly changing conditions of the coastal zone that mainly concern river's curvature, the enlargement of river's width and the shape of lagoons (Georgiou and Mimikou, 2006). Moreover, the extreme meteorological phenomena occurring under the Mediterranean climate of the Arachtos river basin cause significant soil losses, sediments transport with river flow to the reservoir and subsequently their deposition into its dead storage capacity that rapidly decreases the operational and economically effective life time of the project.

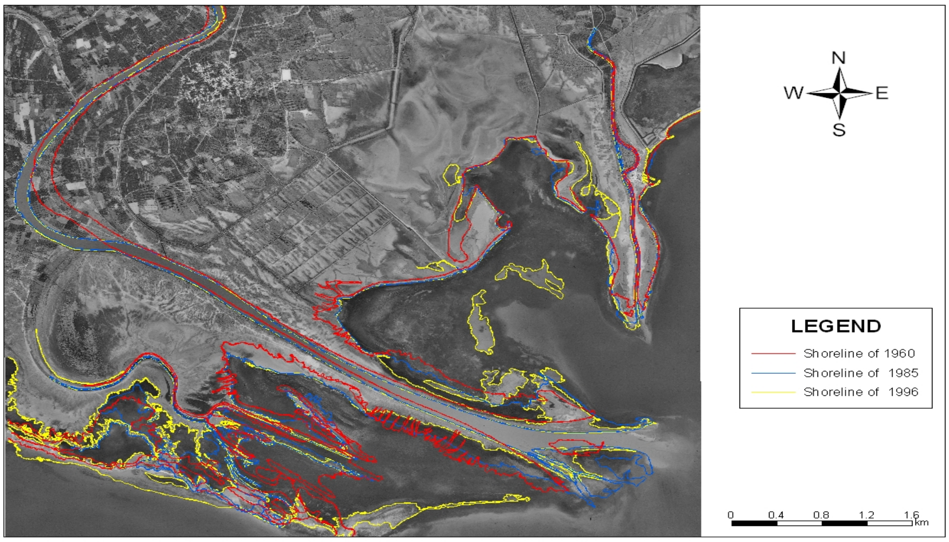

Figure 1. Comparison of digitized shorelines of 1960, 1985 and 1996.

The aim of this paper was to investigate and quantify the reservoir impact on the sediment transport to the Arachtos river delta, heavily affected by the trapping effect, and to propose possible measures capable of reducing the sediment yield, in such a way to prolong the reservoir life.

The catchment was firstly modeled with the GIS-based SWAT (Soil and Water Assessment Tool) model (Arnold et al., 1998) that can predict the impact of many anthropogenic interventions on water and river sediment yields in large complex watersheds. The current modeling consisted of the simultaneous simulation of two different time periods (1964-1980 and 1981-2003), separated by the year 1981, when the Pournari I dam became operational and started influencing the sediment transport processes in the river. Secondly, existing regression formulae were applied in order to check SWAT computations. The first formula calculates river sedimentation rates according to hydrometeorological data of the upstream catchment (Syvitski et al., 2002), while the second predicts sediment yields in cathments with known meteorological and geological characteristics (Koutsoyiannis and Tarla, 1987). The last method relates sediment discharge to precipitation with regression equations calibrated according to gauged data of Northwestern Greece, which also incorporate topographical and geological factors.

To the aim of reducing the sediment yield, so to deal with the problem of reservoir inadequacy in the near future, changes of crop schemes and agricultural practices were then considered. Agricultural land that is usually very susceptible in soil losses was considered to be the most favorable landcover type, where low-cost mitigation measures against erosion can be applied. Land use changes which are biophysically, or more commonly in the last years, artificially based (Skole and Tucker, 1993), often have significant effects on the surrounding environment and consequently on the hydrological cycle. Although the empirical knowledge of the consequences of a land use change is generally common (i.e. crops cultivation under rotations, strip-cropping, contours or terrace systems can decrease soil loss and sediment discharge), it is often very difficult to make an explicit quantification of these consequences. Based on our knowledge in using the SWAT model for different purposes (Mimikou et al., 2000, Varanou et al., 2002, Panagopoulos et al., 2007), a method for quantifying the impacts from specific land use changes, on soil losses of the Arachtos river basin is presented, trying to come to reliable conclusions regarding the implementation of erosion restriction measures on catchment scale. The importance of land uses in the SWAT simulation of erosion and sediments transport lies mainly in the computation of surface runoff with the help of the SCS curve and of soil losses with USLE_C and USLE_P parameters of the Modified Universal Soil Loss Equation (MUSLE) that refer to the landcover type and its support practice respectively (Neitsch et al., 2001).

2. STUDY AREA

The Arachtos river basin (Fig. 2) is located in the western part of Greece. The river drains into the Amvrakikos gulf, a semi-closed marine area of 405 km^2, connected to the Ionian Sea to the West through a narrow natural channel. The climate is of Mediterranean type with temperate winters, high rainfall and sun exposure, with the mean annual temperature and rainfall depth being 15^{o}C and 1500 mm respectively. The watershed has an area of 2000 km^2 and is predominantly agricultural land (arable and pasture). The elevation range is 0 to 2400 m with the mean elevation being 785 m. The length of the main stream is 110 km. High rainfall events in combination with the impermeable soil formations cause significant runoff, high soil losses and river sediment yields. Parts of the watercourse are influenced by man-made interventions, such as the Pournari I dam, which was constructed in the early 80's, located in the homonymous region 3 km upstream of Arta city (Fig. 2). The production of hydropower in the peaks of electric energy demand, the storage of water for irrigation use in the Arta plain and the flood protection constitute the multi-scope of this construction that has a total storage capacity of 865 hm^3 and became operational in 1981.

In 1996, a second smaller dam (storage capacity 5 hm^3), named Pournari II, was also constructed 1.5 km downstream the Pournari I dam with the purpose of distributing the regulated flows from the reservoir to the downstream agricultural areas of the Arta plain, rendering the irrigation operation completely independent from the short term water release fluctuations of the upstream dam operation.

3. SWAT MODEL IMPLEMENTATION

3.1 Swat Model Description

The Soil and Water Assessment Tool (SWAT) is a physical river basin model that was developed for the U.S.D.A. Agricultural Research Service, by the Blackland Research Center in

Texas (Arnold et al, 1998). It predicts the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time. The model is physically based and requires specific information about weather, soil properties, topography and vegetation. SWAT has the ability to divide the watershed into smaller subbasins and subsequently into Hydrologic Response Units (HRUs). An HRU is a unique combination of a land use and a soil type that are overlapped in each subbasin. Simulation of the hydrology of a watershed can be separated into two major divisions. The first division is the land phase of the hydrologic cycle, which controls the amount of water, sediment, nutrient and pesticide loadings to the main channel in each subbasin. The second division is the water or routing phase of the hydrologic cycle, which can be defined as the movement of water, sediments and nutrients through the channel network of the watershed to the outlet (Neitsch et al., 2001).

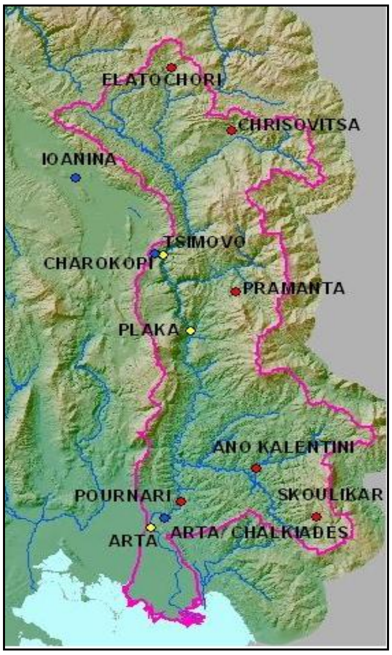

Figure 2. Main locations in the Arachtos river basin.

The hydrologic cycle as simulated by SWAT is based on the water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{\text{gw}}) \tag{1}$$

where SWt is the final soil water content (mm H_2O), SW_0 is the initial soil water content on day i (mm H_2O), t is the time (days), R_{day} is the amount of precipitation on day i (mm H_2O), Q_{surf} is the amount of surface runoff on day i (mm H_2O), E_a is the amount of evapotranspiration on day i (mm H_2O), w_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm H_2O), and Q_{gw} is the amount of return flow on day i (mm H_2O).

Sediment yields are estimated for each HRU with the Modified Universal Soil Loss Equation (MUSLE):

$$sed = (11{,}8 * Q_{surf} * q_{peak} * area_{hru})^{0{,}56} * K_{usle} * C_{usle} * P_{usle} * LS_{usle} * CFRG \tag{2}$$

where sed is the sediment yield on a given day (metric tons), $Qsurf$ is the surface runoff volume (mm H_2O/ha), q_{peak} is the peak runoff rate (m^3/s), $area_{hru}$ is the area of the HRU (ha), K_{USLE} is the

USLE soil erodibility factor, C_{USLE} is the USLE cover and management factor, P_{USLE} is the USLE support practice factor, LS_{USLE} is the USLE topographic factor and *CFRG* is the coarse fragment factor. The values of K_{USLE}, P_{USLE}, C_{USLE} and *CFRG* in a simulation represent the impact of soil and landcover characteristics on soil losses, while LS_{USLE} is automatically defined by the model according to topographical information (Neitsch et al., 2001).

3.2 The Arachtos Model Parameterization

Based on the DEM of 50 x 50 m resolution (Fig. 3a), the model delineated and subdivided the watershed in several smaller subbasins. Ten subbasin outlets were finally selected to be active (Fig. 3d), based on the spatial differentiation of meteorological information and on the location of monitoring stations with available flow and sediment measurements. The landcover map (Fig. 3b) was obtained from the European CORINE project, mainly representing forest (FRST) occupying the 30% of the total area and agricultural land (60%) that was distinct into pastureland (WPAS) and arable land. The latter consisted of vine (VINE), rice fields (RICE), orchard trees (ORCH) and predominantly of row crops (AGRR), that mainly included corn and wheat cultivations. Urban land cover types included the Arta city and many small scattered municipalities within the catchment.

According to the Institution of Geology and Mineral Exploration (IGME), geological formations (Fig. 3c) consisted of flysch deposits that mainly covered the northern part of the catchment, karstic systems of limestones that were encountered in the central part, sandstones, which were impermeable geological formations and alluvium that have been transported and deposited in the Arta plain. Due to the lack of soil studies in the wider area, the major soil properties like texture, hydraulic conductivity, water capacity and the soil erodibility factor K_{USLE} that influence the hydrologic and sediment transport processes, were initialized in the model according to literature and their values were subsequently adjusted during calibration. The HRU's were produced by overlaying the landcover map onto the geological map. For the period 1964-2003, available meteorological data of daily rainfall, air temperature, net solar radiation, wind speed and humidity, obtained from various stations of the Public Power Corporation within the catchment (Fig. 3d), were also inserted. For the estimation of potential evapotranspiration, the Penman-Monteith method was used. Finally, the reservoirs were considered as impoundments on the main river (Neitsch et al., 2001) and were included in the simulation from their starting date of operation by assigning their technical characteristics to the model (reservoir area, total volume etc.).

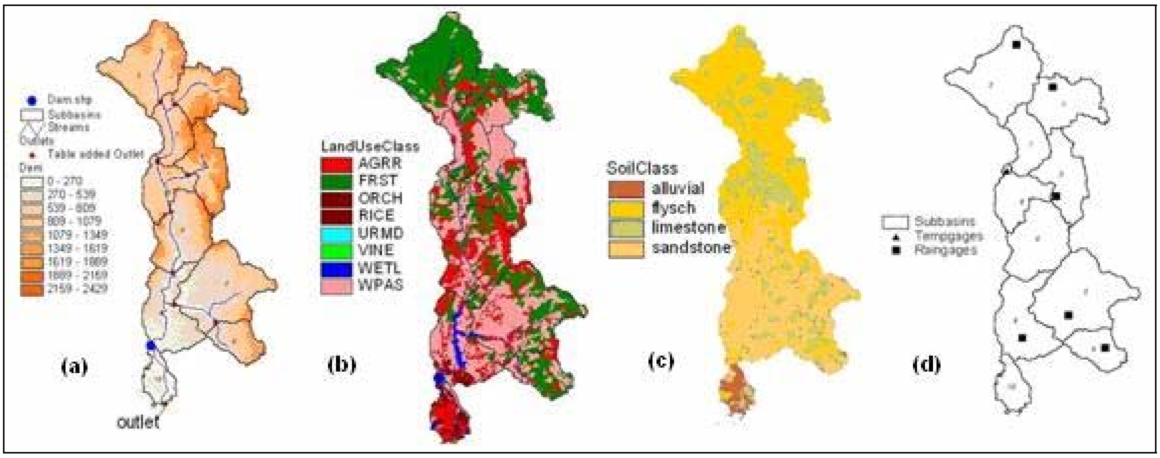

Figure 3. Representation of (a) topography, (b) landcover types, (c) geological formations and (d) watershed delineation and meteorological stations in the catchment.

River sediment yields were estimated primarily by quantifying soil losses from HRU's with equation 2. The values of MUSLE factors for the main landcover and soil types of the Arachtos catchment that were finally determined after calibration are presented in Table 1.

Table 1. Calibration values of MUSLE factors determining soil losses.

MUSLE coef / Landcover type	Forest (FRST)	Arable land (AGRR)	Pasture (WPAST)	Orchard (ORCH)
C_{USLE}	0.001	0.2	0.003	0.001
P_{USLE}	1.00	1.00	1.00	1.00
MUSLE coef / Soil type	Alluvium	Sandstones	Flysch	Limestones
K_{USLE}	0.10	0.20	0.12	0.15
CFRG	10%	10%	10%	10%

The C_{USLE} coefficient is the initial value assigned by SWAT to each landcover type and is updated daily during the simulation according to the growth cycle of the plant and its canopy development. Thus, forest and pasture that both result in dense ground cover, have lower values of C_{USLE} than agricultural land, protecting much more the ground from erosion. P_{USLE}, is defined as the ratio of soil loss with a specific support practice to the corresponding loss with up-and-down slope culture (Neitsch et al, 2001). Because no support practices existed in the Arachtos catchment, P_{USLE} coefficient took its default and maximum value (1.00). Finally, due to the lack of sufficient soil studies in the catchment, K_{USLE} was adjusted during calibration, while for *CFRG* factor the default percentage of soil content 10% was used for all geological formations. From Table 1, it is indicated that C_{USLE} and K_{USLE} are the only factors that govern the erosion susceptibility of the different landcover and soil types respectively.

3.3 Calibration Results for Flows and Sediment Yields

The available measurements of flows and sediments were used for comparison with the computed results in order to test the SWAT simulation efficiency. Hydrological calibration was carried out by adjusting groundwater and soil properties. Sediments calibration was achieved by mainly adjusting the concentration of sediments in subsurface flow and the KUSLE factor of the MUSLE equation (Neitsch et al, 2001). Calibration took place in annual and monthly basis at three sites named Tsimovo, Plaka and Arta (Fig.2), where measures of flow and sediments (1965-1975) existed. Figure 4 represents the graphical comparison between simulated and observed flows and sediment yields in Arta. The Nash-Sutcliffe coefficient of determination (Nash-Sutcliffe, 1987), the Root Mean Square Error (RMSE) and the correlation coefficient between the existing and the simulated time-series of flow and sediments were used to estimate the simulation efficiency. All the indices proved the convergence between measured and simulated yields as they received sufficient values both in monthly and annual basis for the three locations. Flow simulation was more satisfactory than that of sediments as the model could not simulate sufficiently some seasonal high peaks of sediment discharges.

3.4 SWAT Simulation Results

The mean annual precipitated water of the simulation period (1964-2003) approached 1500mm in the Arachtos catchment, and was converted approximately into 450 mm of actual evapotranspiration, 150 mm of percolated water to the deep aquifer and 900 mm of annual runoff. During the period 1964-1980, precipitation was by 200mm higher than during the recent period of 1981-2003. Runoff was of high magnitude, something that was interpreted by the high rainfall depth and by the presence of impermeable geological formations that impeded soil infiltration. For the period 1964-1980 the mean annual runoff was calculated almost 960mm, whereas during the second it approached 830 mm. The mean annual evapotranspiration was estimated nearly 450mm in the first period and 400mm in the recent one, while percolation to deeper layers was consistently insignificant. The relative occurrence of the main components of the hydrological cycle during the two separated time periods was stable, demonstrating the steady behaviour of the catchment.

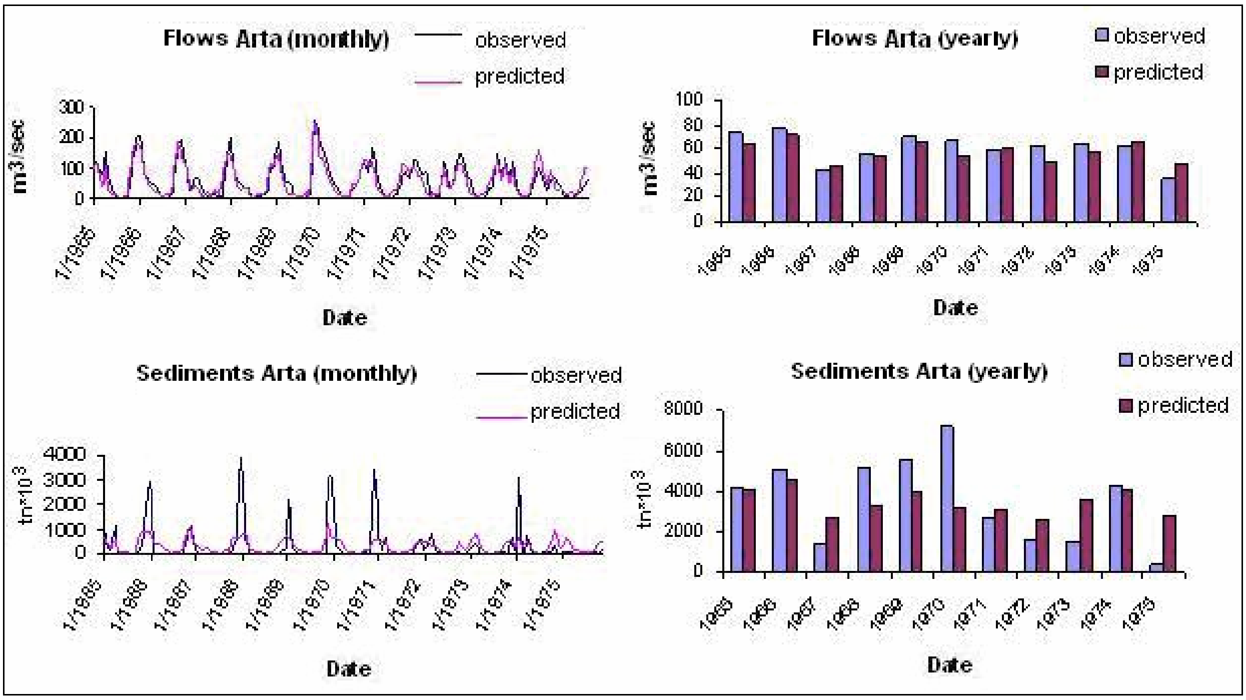

Figure 4. Comparison between observed and simulated flows and sediment yields in Arta.

As indicated in Table 1, C_{USLE} and K_{USLE} of the MUSLE equation were the major factors that governed the erosion susceptibility of the different landcover and soil types respectively. Their annual contribution to soil losses to the river in respect to precipitation received and runoff generated is presented in Figure 5.

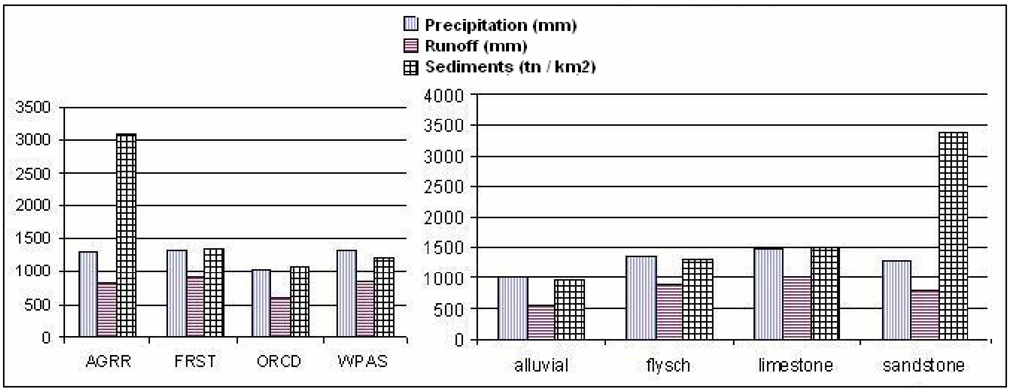

Figure 5. Mean annual soil losses originating from different land cover and geological types.

Arable land of row crops (AGRR) generated the highest soil losses in the catchment, 3100 tn/km^2, while forest (FRST), orchard trees (ORCH) and pasture (WPAS) caused significant lower soil loss and subsequently contributed much less to the river sediment transport as lower values of C_{USLE} were assigned to them (Table 1). On the other hand, sandstones were the most susceptible geological formations in soil loss processes. According to the results, the mean annual erosion rate of sandstones was 3400 tn/km^2, while the respective losses originating from the remaining three formations ranged between 1000-1500 tn/km^2, something that was attributed to their K_{USLE} values adjusted for calibration purposes (Table 1).

The major SWAT simulation results are summarised in Figure 6, which presents the mean annual flows and sediment yields of the periods 1964-1980 and 1981-2003 at four different locations upstream and downstream the reservoir as well as the mean monthly yields of these periods at the outlet.

Mean monthly model results regarding routed flows and sediment yields at the watershed outlet (1964-1980), are presented in Figure 6(c) and 6(d) respectively. River flows and sedimentation rates were maximized during winter months when the maximum precipitation depth also occurred. In November and December, flows exceeded 100 m^3/s (Fig. 6c), when near 600 thousand tons of sediments were transported to the outlet as well (Fig. 6d). On the contrary, during summer months the respective results were at least one order of magnitude lower, revealing that the hydrological regime of the Arachtos catchment is governed by the special characteristics of the Mediterranean climate. On an average hydrological year, 76% of the annual precipitation occurred during the wet period (October-March), causing 80% and 82% of the annual runoff and river sediment yields.

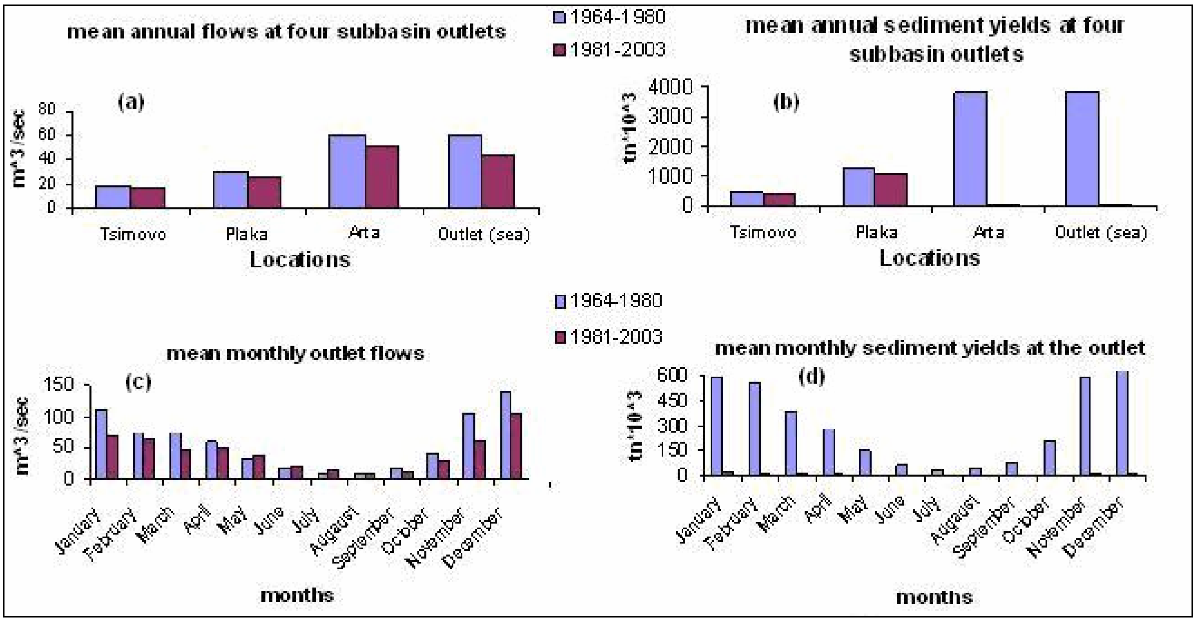

Figure 6. Mean monthly and annual flows and sediment yields for the two periods of interest.

As indicated in Figure 6a and 6b, during the first period of interest (1964-1980), simulated flows and sediments in Arta were routed physically downstream to the outlet. The average annual water flow and sediment yield at the outlet before the dam operation starting (period 1964-1980), was 61 m^3/s (Fig.6a) and $3.7x10^6$ tn/y (Fig.6b) respectively. The annual water flow occurrence during the period 1981-2003 was comparable to that of the period 1964-1980, not only in the upstream locations (Tsimovo, Plaka), but also in Arta and at the watershed outlet that are located downstream the reservoir, indicating that no significant reduction in river flows occurred after the dam construction. This was attributed to the fact that flow regulation for hydropower production allowed water to be routed to the outlet without changing the seasonal flow patterns (Fig.6c). Nevertheless, mean annual flows in all sites (Fig.6a) and mean monthly flows at the outlet (Fig.6c) were somewhat lower during the most recent period, probably due to the decreased annual rainfall.

On the other hand, the sedimentation rates in the downstream part of the catchment have been altered dramatically. As indicated in Figure 6b, annual sediment yields in Arta and watershed outlet were so dramatically decreased that can be considered negligible, while sediment transportation occurred physically in Tsimovo and Plaka that have not been influenced by the dam operation. More specifically, the mean annual sediment yield in Arta referring to the period 1964-1980 was $3.8x10^6$ tonnes with the respective value concerning the period of the dam operation being only $0.064x10^6$ tonnes, a reduction of 98.5%. Sediment discharges at the watershed outlet were almost equal to those in Arta, as the mean annual sediment outflows have been calculated $3.7x10^6$ and $0.085x10^6$ tonnes for the periods 1964-1980 and 1981-2003 respectively, indicating that the downstream the reservoirs part of the catchment ($88km^2$) was insignificantly eroded. This was attributed to the topography of the Arta plain, as gentle slopes restrained soil loss and sediment transport to the outlet. Figure 6d also indicates the significant monthly reduction in sediment transport to the outlet as yields were so much inconsiderable that is practically hard to be discerned in the bar-chart. Finally, the Pournari II reservoir was completely uninvolved in the sediment transport processes as it was receiving insignificant amounts of sediments during its 8-year operation (1996-2003), while water flow was simulated to occur physically through the structure.

4. ESTIMATION OF SEDIMENT DISCHARGE BASED ON PRECIPITATION AND RIVER FLOWS

In order to check the results obtained by means of the SWAT model, two different series of regression formulae were adopted. The first one concerns mathematical formulae that can globally predict the long-term flux of sediments in river basins and was developed by Syvitski et al (2002). Based on geomorphological data, sediment measurements and a formula for estimating mean annual temperature, the following equations for computing sediment loads were developed:

$$Q_s = \alpha_3\, A^{\alpha 4}\, R^{\alpha 5}\, e^{k1T} \quad (3)$$

$$Q_s = \alpha_6\, Q^{\alpha 7}\, R^{\alpha 8}\, e^{k2T} \quad (4)$$

where Q_s is the long term sediment load (kg/s), A is the drainage basin area (km^2), R is the maximum relief from catchment outlet to the mountain top (m), T is the mean annual temperature (^oC) and Q is the average annual water discharge (m^3/s). For the temperate climate zone of the North hemisphere the optimum values of the coefficients α_3, α_4, α_5, α_6, α_7, α_8, k_1 and k_2 were estimated after a multi-regression analysis as follows: α_3=6.1x10^{-5}, α_4=0.55, α_5=1.12, α_6=1.1 x10^{-3}, α_7=0.53, α_8=1.1, k_1=0.07 and k_2=0.06. The application of these equations in Arta, with the necessary parameters being: A=1900km^2, R=2300m, T=15^{o}C and Q=60 m^3/s, gave very satisfactory results. Equation 3 gave Q_s=64.53 kg/s or 2.04 Mtn/y, while the results produced by equation 4 were Q_s=118.2kg/s or 3.73Mtn/y. As SWAT predicted the long-term flux of sediments in Arta 3.8 Mtn/y, it is obvious that the results of the current study fully agree with the Syvitski et al (2002) methodology, especially when the mean annual river flow is used in the multi-regression analysis (Equation 4).

Syvitski et al (2002) also suggest the correction of sediment flux predictions due to the presence of reservoirs in the catchment, by calculating the dam trap efficiency:

$$TE = 1 - (0.05/\Delta\tau_r^{1/2}), \qquad v>0.5\ km^3 \quad (5)$$

where TE is the trap efficiency (%) and $\Delta\tau_r = v/Q$ with v being the volume of reservoir (km^3) and Q the average annual discharge at the mouth of the reservoir (km^3/y). Solving the equation with the known Pournari I reservoir characteristics (v=865x10^6 m^3=0.865 km^3 and Q=60 m^3/s=1.89 km^3/y), the trap efficiency estimation for the reservoir was 92.6%, very close to the predicted by SWAT percentage of almost 98%. A rough estimation of 20 years remaining until the fulfillment of the reservoir dead storage capacity with sediments has been also carried out in a previous work (Panagopoulos and Mimikou, 2006).

The second methodology applied in order to ensure the reliability of the SWAT results, was developed by Koutsoyiannis and Tarla (1987). It was based on the investigation of the effects of hydrological, climatic, topographical and geological factors on sediment yields, based on the gauged data of Northwestern Greece. The results have shown that sediment discharge per unit area is strongly related to precipitation and soil characteristics according to the following equation:

$$G = a * \gamma * e^{bP} \quad (6)$$

where: a, b: constants, G (t/km^2): average (monthly or annual) sediment discharge, P (m): monthly or annual precipitation and γ: geological co-efficient. The empirical geological co-efficient γ is the average potential erosion rate and is related to the potential erosion rate of each specific soil type by the following equation:

$$\gamma = k_1*p_1 + k_2*p_2 + k_3*p_3 \quad (7)$$

where: k_1 is the coefficient for soils of high erosion (alluvium deposits, sandstones etc), k_2 for soils of moderate erosion (flysch etc), k_3 for soils of low erosion (limestones etc) and p_1, p_2, p_3 refer to the proportion of each soil type in the entire river basin. The parameters a, b and γ were estimated by using a non–linear optimization algorithm (Koutsoyiannis and Tarla, 1987).

The algorithm has been calibrated on a monthly basis in Tsimovo, Plaka and Arta sites, where measures of sediment discharges existed. The comparison between the observed and simulated sediment discharge was evaluated by the Nash-Sutcliffe coefficient of determination (Nash-Sutcliffe, 1987) and the correlation coefficient. Both indices assumed sufficiently high values that gave evidence for the success of the simulation. The Nash coefficient received values above 0.30 while the correlation coefficients ranged between 0.60 and 0.70, showing an acceptable convergence between measured and simulated sediment discharges at the three measuring stations of the watershed. The final form of equation 6 for each measuring station was the following:

$$G = 60.5 * 0.49 * e^{5.74P} \quad \text{for Tsimovo station}$$

$$G = 78.63 * 0.64 * e^{5.60P} \quad \text{for Plaka station}$$

$$G = 74.4 * 0.89 * e^{5.95P} \quad \text{for Arta station}$$

The total amounts of sediments calculated in each site are summarized in Table 2 together with the site of Pournari I dam that is located a few kilometers upstream of the Arta measuring station, in the last column. Sediments at this site were calculated by considering a linear change of sedimentation rates between the two sites according to the catchment areas defined by their locations. Thus, as the catchment area upstream of Pournari I dam location is 1800 km^2, 55 km^2 less than this in Arta, the total amounts of sediments at the dam site were calculated as a percentage of 97% of those in Arta. In the last table row the mean annual sedimentation rate in Mtn/y is given for the period of interest.

Table 2. Total sediment yields during the period 1964-1980 and mean annual sedimentation rates across the river.

Period	Tsimovo	Plaka	Arta	Pournari I
1964-1980 (tn)	7.236.820	22.444.128	61.966.982	60.107.973
1964-1980 (Mtn/yr)	0.43	1.32	3.65	3.54

By comparing the total amount of sediments that were estimated from this optimization algorithm and the SWAT model, the deviations do not exceed a 10%. The mean annual sedimentation rate of the period 1964-1980 in Arta was calculated 3.8 Mtn/y by SWAT, while the previous methodology led to almost the same estimation (3.65 Mtn/y). Taking also into consideration the calculation according to Syvitski et al (2002) methodology (3.73Mtn/y) and that the mean annual measured sediment discharge was 3.6 Mtn/y it can be concluded that all methodologies led to acceptable computations. Although the formula of Koutsoyiannis and Tarla (1987) gave the least deviation from the mean observed value, deviations arising by the other methodologies are so small as well that a clear conclusion for the most accurate method can not be drawn. However, it can be concluded that sediment discharges can be adequately predicted according to hydrological, meteorological, topographical and geological data, and as the current results indicate, even the existence of only the last three data types, always available for Greek catchments, is sometimes adequate for accurate estimations.

Finally, the dam trap efficiency was once more estimated using the Brune diagram and information on the particles size and the fraction of dam storage to the mean annual volume of water that pours into the dam (Morris and Fan, 1998). The fraction of capacity/mean annual flow gives a value of 0.6 in the x-axis of the Brune diagram that corresponds to a trap efficiency of approximately 98%. The result showed that only a minor proportion of total sediments (less that 2%) end up downstream of the dam and eventually are transported to the river's delta, something that is in full agreement with SWAT estimations. From 1997, when Pournari II dam started operating just downstream of the first dam, sediments that end up to the delta can be considered negligible.

5. LAND USE CHANGE SCENARIOS

5.1 Scenarios Building

High sedimentation rates of the Arachtos river demonstrated the need for the application of mitigation measures against erosion in the catchment. Thus, we tried to assess the impact that land use changes had on sediments discharge, in terms of quantifying the results from pre-specified scenarios. Such scenarios are feasible because of their low-cost and non-structural character when implemented as special management practices on parts of the agricultural land.

In Figure 3(b) AGRR represented the part of the arable land (almost the 30% of the agricultural land and 20% of the catchment area) that was subject of the scenario applications. As this part of the catchment was covered by row crops, especially corn and wheat, it was the most appropriate for the application of realistic scenarios, in contrast to the other arable land types of permanent cultivations (e.g. orchard trees, vines), where no realistic scenarios of land use change could be easily applied. The re-creation of the mgt files was made according to the theoretical base of SWAT (Neitsch et al, 2001). The model was executed for the period 1964-1980, by keeping the same set of all other model parameters of the original calibration, giving river discharge outputs in Arta. These outputs were then compared to the respective ones of the base run with the purpose of estimating the decrease of sediments transport to the reservoir, thus estimating the percentages of discharge change for every scenario.

Land use changes referred to the application of crop rotations and special cultivation techniques. Three rotations consisting of corn-wheat, corn-hay and wheat-hay were firstly examined. The first scenario was a two-year rotation of corn-wheat cultivation started with corn sowing on 10 April, harvest on 10 September, a soil tillage in the middle September and finalized by wheat sowing at the end of the same month with harvest at the end of August of the second year. The second rotation scenario also consisted of corn cultivation with the difference that three years of hay cultivation followed it. The third one was similar to the second but with winter-wheat, instead of corn, being the crop in the four-year rotation. By incorporating corn and/or wheat in all applied rotations (the existing crops in the area), scenarios reliability is further strengthened as these remedies can to a large degree be considered socially and financially feasible. The next step was to look for the combination of rotation and support practises (contours, strip-cropping on the contour and terraces) that was the least susceptible to erosion.

The land cover and management factor C_{USLE} as well as the support practice factor P_{USLE} were the two components of the M_{USLE} equation that reflected the land use change information in SWAT. Crop rotations and different cultivation techniques resulted respectively in the modification of the aforementioned indices that subsequently caused changes in soil losses generated by each HRU. The C_{USLE} factor was automatically modified according to the assigned respective value in the landcover / plantgrowth database of SWAT, while P_{USLE} was modified according to the basis described in SWAT theoretical documentation for land slopes between 1% and 2% (Neitsch et al, 2001). Table 3 summarises the values that the two aforementioned factors received in each scenario.

Table 3. C_{USLE} and P_{USLE} values of agricultural mgt files under six scenarios and the base run.

	Base run	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Crop rotation	AGRR - no rotation	corn - wwht	corn - hay	wwht - hay	wwht - hay	wwht	wwht - hay
Cultivation - Technique	none	none	none	none	contours	terraces	strip-cropping
C_{USLE}	0.2	0.2 - 0.03	0.2 - 0.003	0.03 - 0.003	0.03 - 0.003	0.03 - 0.003	0.03 - 0.003
P_{USLE}	1.00	1.00	1.00	1.00	0.60	0.50	0.30

5.2 Results of the Scenarios Application

Mean annual sediment yields in Arta (approximately at the reservoir site) and the percentage of annual change in the river yield, caused by each scenario, are presented in Figures 7(a) and 7(b) respectively.

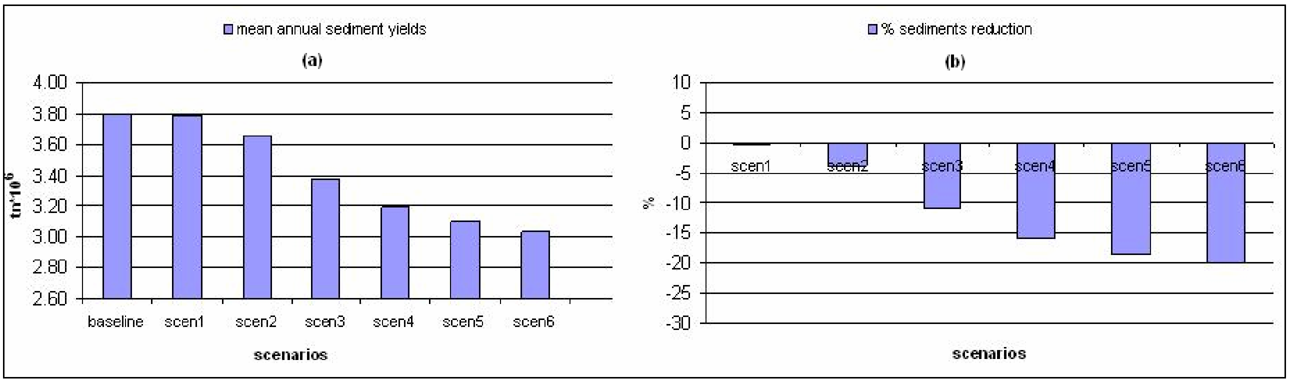

Figure 7. Mean annual sediment discharges in the reservoir under the existing situation and six different land use change scenarios (a) and the percentage of change in annual yield caused by each scenario (b).

From the above Figure it is firstly concluded that the effects from the rotated cultivation of corn and winter wheat (scen. 1) can be nearly neglected. Although winter wheat reduced the C_{USLE} coefficient, the presence of corn, even in only one of the two years rotation, was restrictive for sediments reduction. On the other hand, winter wheat and hay (scen. 3) was the most effective rotation in decreasing soil losses from the arable land as the annual sedimentation rate of 3.8 Mtn/y of the baseline was reduced to 3.38 Mtn/y, a reduction of 11%. This change can be firstly attributed to the reduced C_{USLE} factors of winter wheat and hay in relation to this of the row crops (AGRR) that existed during the baseline and secondly to the reduced surface runoff generated by hay, as for that type of landcover, lower CN values were also assigned by the model (Neitsch et al, 2001). Corn-hay cultivation (scen. 2) also resulted in an intermediate reduction of almost 4%. Further application of the most effective scenario on sediments reduction (scen. 3), with the incorporation of specific support practices, significantly improved the results. The rotation of winter wheat and hay on contour tillage and planting cultivation reduced annual sedimentation rates by 16% due to the decreased P_{USLE} factor that received the value of 0.6. When winter wheat was cultivated under strip-cropping on the contour (scen. 6), meaning that strips of winter wheat were alternated with equal-width contoured strips of sod, the P_{USLE} factor was minimized, receiving the value of 0.30 that resulted in the greatest reduction (20%) in annual river sediments yield (3.04 Mtn/y). When winter wheat was cultivated in terraced fields (scen. 5), a significant reduction of 18.5% in sediment yields also occurred as we reduced the P_{USLE} factor to the value of 0.50.

6. CONCLUSIONS AND OUTLOOK

Soil losses from different geographical units of the Arachtos catchment as well as river sediment yields were sufficiently quantified by implementing the SWAT model and regression formulae that related hydrometeorologic and/or geomorphologic catchment characteristics to sediment discharges. The results led to a significant average annual sedimentation rate near the Pournari I dam location ranging between 3.65-3.80 Mtn/y. The dam trap efficiency was also estimated over 90% demonstrating that the available reservoir dead storage capacity for sediments deposition is rapidly decreased. However, the modeling of low-cost land use change scenarios including crop-rotations and specific support practices on parts of the agricultural land seemed to be efficient and feasible mitigation measures against erosion. The results strongly suggested the incorporation of hay cultivation in the arable land of the catchment under rotation with one of the existing row crops (corn, wheat). Especially, the cultivation of hay and winter wheat under the strip-cropping support practice resulted in 20% annual reduction in sediment yields in the reservoir, a percentage that in combination with other mitigation options related to reservoir management can prolong the project life with operational, economical and environmental benefits. On the other hand, changes on the coastal zone, mainly concerning river's curvature and the shape of lagoons have affected the social community during the last years and can be only confronted with the adoption of hard policy choices like the opening of dams or with high-cost structural interventions.

REFERENCES

Arnold, J.G., R. Srinivasan, R.S. Muttiah, and J.R. Williams. 1998. Large area hydrologic modelling and assessment part I: model development. *J of Amer. Water Resource Assoc.* 34(1): 73-89.

Bonora, N., F. Immordino, C. Schiavi, U. Simeoni, and E. Valpreda. 2000. Interaction between catchment basin management and coastal evolution (Southern Italy). *J. of Coastal Res. - Northern Ireland*. 36: 81-88.

Georgiou E. and M. Mimikou. 2006. Integrated Methodologies for the mapping of costal evolution due to the man-made interventions in the Arachtos River Basin. *J of WSEAS Transactions on Environment and Development*, 2(4): 375-382.

Kapsimalis, V., C. Tziavos, I. Livanos, and C. Anagnostou. 2002. *The new mouth of the Arachtos river (NW Greece). Factors affected the geomorphological evolution.* A study of Greek Maritime Research Centre and Institute of Oceanography.

Koutsoyiannis, D., and K. Tarla. 1987. Sediment Yield Estimations in Greece, *Technica Chronica Journal.* A-7(3): 127-154.

Morris, G.L., and J. Fan. 1998. *Reservoir Sedimentation Management: Design and Management of Dams, Reservoirs, and Watersheds for Sustainable Use*. United States. McGraw-Hill.

Mimikou, M., E. Baltas, E. Varanou, and K. Pantazis, 2000. Regional impacts of climate change on water resources quantity and quality indicators. *J. of Hydrol.* 234: 95-109.

Nash, J.E., and V. Sutcliffe. 1970. River flow forecasting through conceptual models, I. A discussion of principles. *J. Hydrol*. 10: 282-290.

Neitsch, J.G., J.G. Arnold, J.R. Kiniry, and J.R. Williams. 2001. *Soil and Water Assessment Tool, Theoretical Documentation - Version 2000*. Blackland Research Center – Texas.

Panagopoulos, I., and M. Mimikou. 2006. Assessment of the changes in the arachtos river flow and sediment discharges due to anthropogenic interventions. In *Proc. Protection and Restoration of the Environment VIII*, 3-7 July 2006, Chania, Greece.

Panagopoulos, I, M. Mimikou, and M. Kapetanaki. 2007. Estimation of nitrogen and phosphorus losses to surface water and groundwater through the implementation of the SWAT model for Norwegian soils. *JSS - J Soils & Sediments* 7(4): 223-231.

Skole, D., and C. Tucker. 1993. Tropical deforestation and habitat fragmentation in the Amazon: satellite data from 1978 and 1988. *Science* 260:1905-1910.

Syvitski, J.P.M., S.D. Peckham, R. Hilberman, and T. Mulder. 2003. Predicting the terrestrial flux of sediment to the global ocean: a planetary perspective. *Sed. Geol* 162: 5-24.

Varanou, E., E. Gkouvatsou, E. Baltas and M. Mimikou. 2002. Quantity and quality integrated catchment modelling under climatic change with use of soil and water assessment tool model. *J. Hydr. Eng.* 7(3): 228–244.

Verburg, P.H., G.H.J. Koning, K. Kok, A. Veldkamp, L.O. Fresco, and J. Bouma. 1999. *Quantifying the spatial structure of land use change: an integrated approach.* Agricultural University, Wageningen, The Netherlands.

Walling, D.E. 1999. Linking land use, erosion and sediment yields in river basins. *Hydrobiol.* 410: 223-240.