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Sediment Delivery Assessment for a Transboundary Mediterranean Catchment: The Example of Nestos River Catchment

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Abstract Nestos River flows through Bulgaria and Greece and discharges into the North Aegean Sea. Its total catchment area is around 6,200 km^2, while the mean annual precipitation and runoff are 680 mm and 40 m^3/s, respectively. The Hellenic part of the catchment has undergone a substantial hydroelectric development, since two dams associated with major hydropower pumped-storage facilities are in operation. The main objective of the paper is to assess the expected sediment delivery of Nestos R. at the uppermost Thisavros reservoir site. This has been carried out by implementing the Universal Soil Loss Equation in a GIS environment for determining the mean annual soil erosion in conjunction with a suspended sediment measurement program (114 measurements in total) accomplished between 1965 and 1983 adjacent to the dam site. The sediment discharge rating curve between sediment and river discharges in a power form has been constructed using five alternative techniques, namely (a) the linear regression of the log-transformed variables, (b) the same as (a) but with the Ferguson correction, (c) different ratings for the dry and wet seasons of the year, (d) the nonlinear regression, and (e) the broken line interpolation that utilizes different rating parameters for two discharge classes. It is shown that the mean annual sediment yield is almost equal for all rating curve formulations and varies between 178.5 tkm^{-2} and 203.4 tkm^{-2} and the highest value results from the broken line interpolation method. Accordingly, the sediment delivery ratios vary slightly between 17% and 19% of the upstream soil erosion.

Keywords Nestos River · Rating curves · Sediment yield · Soil erosion

1 Introduction

Predicting the sediment discharge of a river section or the sediment yield of an upstream catchment has always been an ambitious goal for a number of different earth scientists, such

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as engineers, hydrologists, geomorphologists and others. In particular, estimation of sediment discharge in different temporal and spatial scales is a vital key point for the assessment and design of major hydraulic systems, such as irrigation dams, hydroelectric projects and flood attenuation structures. It is estimated that throughout the world, there are probably more than a few million small ponds up to several thousand cubic metres volume of stored water (Verstraeten and Poesen 2000; de Vente et al. 2005; Renwick et al. 2005) as well as 39,000 large dams (Takeuchi et al. 1998; WCD 2000). Renwick et al. (2005) suggested that only in the conterminous USA the total number of small ponds may be as large as 8–9 million that capture an estimated 21% of the total drainage area, representing 25% of total sheet and rill erosion.

It is estimated that the annual storage capacity loss of the world's reservoirs due to sediment deposition is around 0.5–1% (WCD 2000). For many reservoirs, however, annual depletion rates are much higher and can go up to 4% or 5%, such that they lose the majority of their capacity after only 25–30 years (de Vente et al. 2005). Moreover, it is well demonstrated (e.g. Zarris et al. 2002; Snyder et al. 2004) that in large reservoirs with infrequent drawdowns the majority of the deposited sediment load occupies portions of the useful storage, whereas the dead storage (i.e. the part of stored volume of water beneath a certain reservoir level) is almost free of sediments. This accumulation pattern in large reservoirs poses a serious threat to the sustainability of major hydraulic systems. Two main concerns regarding sediment yield modeling and designing large scale hydraulic systems are: (a) to reliably predict sediment yield at the catchment scale and understand which factors affect the sedimentation rate of reservoirs, and (b) to simulate the correct accumulation pattern in the reservoir in order to optimize the placement of the outlet works. For instance, Zarris et al. (2002) conducted a comprehensive hydrographic survey of the 4,495 hm^3 Kremasta Reservoir in Western Greece in order to determine the accumulated sediment load after 34 years of the reservoir's operation. The total deposited sediments' volume was computed equal to 70 hm^3, whereas the corresponding estimation published in the final design study of the project for 50 years projection time is equal to 394 hm^3 (ECI 1974). The significant overestimation of the expected sediment load is practically a significant waste of valuable natural resources as dead storage volume is inactive in terms of water usage. Moreover the accumulated sediments occupy part of the reservoir's useful storage expanding the total loss of stored water. Therefore, the knowledge of a catchment's sediment yield and sediment distribution in a reservoir will allow estimating the probable lifespan of a reservoir and moreover to take proper measures against reservoir sedimentation, watering shortage and river bank erosion. At the moment, the prediction of sediment yield at the catchment scale (>50 km^2) is still one of the most crucial challenges in sediment yield research.

The objective of the research described herein is to make conjunctive use of soil erosion estimates and insufficient suspended sediment discharge measurements in order to assess the sediment delivery and the associated soil degradation of a hydrologic system with Mediterranean type climatic characteristics. The main purpose of this paper is to primarily focus on the sediment yield estimates by exploiting the information contained in the simultaneous measurements of stream and suspended sediment discharge and to evaluate sediment delivery estimates by a comparison with the catchment's mean annual soil erosion. Sediment yield is computed by means of a suspended sediment rating curve of simultaneous observations of sediment and river discharges and its application to the mean daily discharge time series. Soil erosion, on the other hand, is computed by the application of the well-known Universal Soil Loss Equation (USLE) in a GIS platform. Against the objective of this paper, a significant number of researchers have expressed serious doubts about the validity and usefulness of these methods to assess a catchment's sediment yield (Kirkby 1980; Walling and Webb 1988; Crowder et al. 2007). It will be proved, however, that both suspended sediment rating curves and the USLE for the estimation of sediment yield and soil erosion, respectively, despite their shortcomings, can form a good basis for estimating the suspended sediment delivery of a large scale hydrologic catchment with limited data sets even under Mediterranean climatic characteristics.

2 Materials and Methods

Research on soil erosion and sediment yield modeling is today focused on developing robust tools for calculating sediment yield from intense storm events. This necessity is strongly dictated in Mediterranean-type catchments, where the severity of intense storm events significantly enhances the transport capacity of the river flow maybe beyond the sediment supply (i.e. wash load) and the majority of the annual sediment load may be transported within a few storms in a given year. However, in most engineering applications, the issue of soil erosion and sediment transport is restricted to estimate long-term average values for design and management purposes, e.g. predicting future siltation in reservoirs or total amount of material transport to river mouths for pollution control (Walling 1983; Zarris et al. 2002). This is clearly a problem of scale in hydrology. A consistent basis of understanding the complex processes around all scales is needed from one extreme of erosion plots from one single storm to the long-term sediment yield rates for, say, a whole continent. Most of our knowledge originated from simple experimental plots where it is possible to make reliable estimates maybe for the next few years. It is arguable, however, if this understanding is suitable when scaling up from experimental plots to catchments of thousands of square kilometers, where the long-term average values are most often needed.

On this scale, detailed data on hydrology, meteorology, geology and land use are generally scarce even in technologically developed countries despite the rapid development of Geographical Information Systems (GIS) and Remote Sensing techniques. In this case, the use of comprehensive computer models, based on a distributed approach to hydrologic processes modeling including soil erosion and sediment yield, may be ineffective and the use of empirical and/or lumped approaches, such as the USLE and/or the sediment rating curve, is preferred. For instance, Goodrich and Woolhiser (1991) stated that in large catchments hydrologists are unable to understand and mathematically describe the complex physical processes. Jakeman et al. (1999) noted that the difficulties in environmental modeling can be characterized as problems of natural complexity, spatial heterogeneity and the lack of available data. Therefore, in large catchments, it is most likely that simple models will perform better than a comprehensive modeling approach. The origin of this hypothesis comes from the fact that the empirical introduction of the model parameters is inevitable to induce errors that may not be less than by a simple and lumped approach. Refsgaard (1994) applied a lumped conceptual model, a distributed model of moderate complexity and a distributed model of very high complexity to three African catchments ranging from 254 to 1,040 km^2. A type of validation procedure consisted of calibrating the models on a wet period and validating them on a dry period. Under these conditions, the lumped conceptual model was more accurate than the distributed models. In light of these results, Refsgaard (1994) recommended that the lumped conceptual model, being the easiest to apply, should be chosen over the other distributed models when calibration data are available. Moreover, Kokkonen and Jakeman (2001) compared metric and conceptual approaches to rainfall-runoff modelling in terms of calibration and simulation performances and parameter invariance. This was investigated by applying two models of equal complexity (i.e. possessing the same number of parameters), but with different levels of "conceptualization" to two catchments with different climatology. The results suggest that the model with less conceptualization provides, in general, a more accurate streamflow reproduction, even on independent data sets, but this difference only becomes clear when models are applied to the drier catchment.

Focusing entirely on sediment yield models, an important limitation of applying the available process-based and distributed models has been the lack of data for model parameterisation, validation and, more particularly, for validating the spatial pattern of sediment redistribution within a large catchment. Pickup and Marks (2001) identified that most work on spatially distributed patterns of sediment movement has been undertaken on hillslope or small catchment scales. Scaling up to much larger drainage basins has been proved problematic due to the difficulty in obtaining and verifying information on sediment sources, paths, transport rates and delivery. This is actually the reason why physically-based, distributed models are mostly applied to small catchments, for example: WEPP (Laflen et al. 1991), LISEM (De Roo 1998), EUROSEM (Morgan et al. 1998) and PSED (Chen et al. 2010). Natural systems, from plot to catchment scale, tend to show a great deal of variability. In sediment yield models, assumptions of homogeneity in topography and soil characteristics, for example, are employed frequently. Thus, model predictions are subject to errors as a result of the inconsistency of scale between measured parameters and the way they are used in the model. This problem is particularly evident in data-intensive models.

The suspended sediment rating curves, although an empirical model, are a lumped procedure since a single sediment discharge measurement represents the integration of a number of physical processes and their interactions both in time and space without accounting for these processes at all. The USLE, despite the introduction of many GIS applications that calculate soil erosion in a cell to cell basis, is practically a lumped approach since soil erosion within a catchment is calculated eventually as the average of the i corresponding values where i is the total number of cells that comprise the catchment in question.

2.1 The Universal Soil Loss Equation (USLE)

The USLE (Wischmeier and Smith 1965, 1978) is a simple empirical model, based on regression analyses of soil loss rates on experimental erosion plots in the USA. The model is designed to estimate long-term mean annual erosion rates on agricultural fields. Although the equation has many shortcomings and limitations, it is still widely used because not only of its relative simplicity and robustness but also because it represents a standardized approach.

Soil erosion is estimated using the following empirical equation:

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \tag{1}$$

where A is the mean annual soil loss [t ha^{-1}], R is the rainfall erosivity factor [MJ mm ha^{-1} h^{-1}], K is the soil erodibility factor [t h MJ^{-1} mm^{-1}], L is the slope length factor [-], S is the slope gradient factor [-], C is the cover management factor [-] and P is the conservation practice factor [-]. The numerical values of the different factors of the equation have been computed after processing data collected from thousand of small experimental plots in the USA. This obviously suggests a weakness of the method in case of applying it elsewhere with different climatic and topographic conditions. Additionally, USLE does not account for sediment transport in streams and eventually does not compute sediment yield in large scale catchments. However, in terms of computing only the catchment soil erosion, USLE is a quite satisfactory preliminary approximation. The USLE has been widely applied at a watershed scale on the basis of lumped approach (Williams and Berndt 1972, 1977; Griffin et al. 1988) or on a distributed approach where catchments have been subdivided either into cells of a regular grid or into units where a unique runoff direction exists (Julien and Frenette 1987; Wilson and Gallant 1996; Kothyari and Jain 1997; Onyando et al. 2005; Wu et al. 2005; Bhattarai and Dutta 2007; Chou 2010). Renschler et al. (1997) used USLE model and RUSLE to predict the magnitude and spatial distribution of erosion within a GIS (Geographic Information System) environment using ILWIS software in a catchment of 211 km^2 at grid resolution ranging from 200 m to 1 km. They found simulation of erosion process at grid sizes ranging from 200 to 250 m to be more reasonable. This implies that more detailed grids give better results, as more comprehensive information on geomorphologic characteristics can be acquired at this scale. Spatial prediction of a variable implies that estimates of this variable can be derived at any location or sub-areas. USLE model applications in the grid environment with GIS would allow analyzing soil erosion in much more detail since the process has a spatially distributed character. The recent advances in remote sensing technology have provided very useful methods of surveying, identifying, classifying and monitoring several forms of earth resources and had lead researchers to join USLE with remote sensing data and GIS (Pandey et al. 2007; Dabral et al. 2008; Ismail and Ravichandran 2008; Jain and Das 2010). Remote sensing data provide accurate, timely and real time information on various aspects of the watershed such as land use/cover, physiography, soil distribution, drainage characteristics etc. It also assists in identification of the existing or potential erosion prone areas and provides data inputs to many of the soil erosion and runoff models.

It is obviously more reasonable to use the USLE on a spatially distributed modeling scheme than to apply it to an entire catchment as a lumped model. In this respect, USLE can be a spatially semi-distributed model if only joined with a sediment routing algorithm that routes sediment down the hydrographic network of the catchment. For instance, Mutua et al. (2006) applied the Revised Universal Soil Loss Equation (RUSLE) and the Hillslope Sediment Delivery Distributed (HSDD) model embedded in a GIS environment to calculate soil erosion and sediment yield for the Masinga Catchment in Kenya without calibration or verification data. The HSDD model estimates the sediment delivery ratio on a cell-by-cell basis using the concept of runoff travel time as a function of catchment characteristics. Almost the same approach was followed by Jain and Kothyari (2000) in two catchments in India for estimating sediment yields from selected storm events. In addition to the single use, the USLE have been applied as one component in the water quality models, such as AGNPS (Young et al. 1994), in which the rainfall-runoff model is used to calculate the surface runoff and prepare hydrologic parameters for simulating erosion and sediment transport. Broad applications of these water quality models in basins around the world imply that by integrating with a proper hydrological model, the USLE model or its modified versions may be used for predicting soil erosion at different basin scales. For instance, Wang et al. (2009) incorporated USLE into the BTOPMC hydrologic model and were applied to simulate the river discharges and sediment yields for 29 storm events in the Lushi basin, China. Bhunya et al. (2010) incorporated the Modified USLE (Williams 1975) into a simple conceptual model of sediment yield based on Soil Conservation Service Curve Number (SCS-CN)method, instantaneous unit sediment graph (IUSG) method, and power law and its performance is tested using real field data of the 452 km^2 Chaukhutia catchment in India from storm events.

Since rainfall is the driving force of soil erosion and land degradation, the *R*-factor is the most critical to be computed. The erosivity factor of rainfall is a function of the falling raindrop and the rainfall intensity and is the product of the raindrops' kinetic energy and the 30-minute maximum rainfall intensity. The parameter *R* represents only the rainfall kinetic energy and does not account for the runoff shear stress induced erosion. Van der Knijff et al. (2000) stated that in Tuscany, Italy, the *R*-factor is related to mean annual rainfall *P* (mm), so that *R* can be approximated by the equation:

$$R = aP \tag{2}$$

where *R* is expressed in units of MJ mm ha^{-1} h^{-1} and coefficient *a* ranges from 1.1 to 1.5. They also stated that this equation is based on rainfall data from 25 locations, with *P* ranging from 600 to 1,200 mm. Extrapolating the formula to cover the whole of Italy and other parts of Mediterranean Europe is not wholly appropriate, because the characteristics of rainfall in Tuscany are not representative for other parts of the region. Nevertheless, using the 'Tuscan equation' may be justified because it is based on a wide range of annual rainfall amounts, so it may be more representative than it appears at first sight. Moreover, the erosion assessment presented in this study aims at giving an overview of overall patterns of erosion potential in a large catchment, rather than making detailed quantitative soil loss predictions. Therefore, the equation may be "fit for purpose". In the present study, soil erosion was computed using a GIS implementation of the USLE. The graphical interface is called SEAGIS (after Soil Erosion Assessment using GIS) and was originally developed at the Danish Hydraulic Institute (DHI 1999).

2.2 Suspended Sediment Rating Curves

The statistical expression of suspended sediment and stream discharge is called a sediment discharge rating curve and most commonly takes the power-law form of:

$$Q_s = aQ^b\eta \tag{3}$$

where Q_s is the sediment discharge (kg s^{-1}), *Q* is the river discharge (m^3 s^{-1}), *a* and *b* are the sediment rating coefficient and exponent, respectively, usually estimated by (log) linear regression-least squares, and η is the multiplicative error term which theoretically exhibits a lognormal distribution (Ferguson 1986). The exponent parameter, *b*, is very important when determining the sediment yield of a catchment and it normally assigns values between 0.5 and 3; the higher the parameter the more effective transport capacity of the river flow. Such simple statistical models are attractive to use for several reasons, but, as Colby (1965) points out, daily sediment discharges computed from sediment rating curves may be more accurate than those that are computed from daily samples. As Cohn et al. (1992) explained, daily observations of sediment discharge are subject to the sampling error of a single observation, while the model estimates are based on the whole data set. However, it is now well documented that sediment yield estimates based on rating curve calculations will in most cases involve greater error than those obtained from direct measurements and this can be ascribed primarily to the scatter associated with the rating relationship. Several researchers (e.g. Walling 1977; Asselman 2000; Syvitski et al. 2000) have analyzed such scatter in detail and have described controls associated with season, water temperature, hysteretic effects related to rising and falling stage of the hydrograph, exhaustion effects and varying patterns of tributary inflow. The mathematical technique which is used to construct the rating curve and the adequacy of the number of data points have also been shown to be significant controls on the accuracy of resultant calculations of sediment yield. As a result, the log-linear rating curve model (such as Eq. 3) fails to capture the complete structure of the sediment discharge-flow rate relationships, warranting its modifications depending upon the situation at hand (Sivakumar and Wallender 2004). Such modifications include use of separate curves for different seasons (Mimikou 1982), stratifying the data according to the magnitude of flow and applying a separate curve for each stratum (Glysson 1987), and use of a single multivariate model instead of multiple rating curves (Cohn et al. 1992). In essence, as of now, an acceptable "universal" statistical relationship between the components of the sediment transport system does not exist. In sight of the above, Ferguson (1986) showed that this technique leads to an underestimation of the sediment discharges which is proportional to the variance of the additive error terms. This is because the power function regression curve must go through the arithmetic means of the available data, whereas the detransformed logarithmic regression curve must go through the geometric means that are systematically lower than the arithmetic means. The expected value of the multiplicative error terms is $E(\eta_i)=\exp(2.65\sigma^2)$, where σ^2 is the mean square error of the log-transformed regression, which is greater than zero unless there is no scatter between the rating curve ($\sigma^2=0$) and it becomes higher when the deviation increases. This means that the rating curve actually underestimates the true suspended sediment load in rivers and this underestimation grows particularly in wash load conditions. Ferguson (1986) argues that when the rating parameters are resulted from a log-log regression between suspended sediment and river discharges, a correction factor equal to $2.65s^2$ (where s is the unbiased estimator of σ) should be applied. Another point of interest in determining the sediment rating curves that has not attracted much attention in the past is the definition of outliers. Unlike stage—discharge rating curves, where the hysteretic effects (same stage at different discharges for the rising or falling part of the hydrograph) do not deviate significantly from the general curve, suspended sediment discharge is less dependent on the explanatory variable (river discharge) and the scatter of measurements around the regression line is always significant. It is a common situation that for the same river discharge, sediment discharges could deviate by at least two orders of magnitude or even more. Therefore, the rate of suspended sediment transport depends largely on the sediment supply and availability in the catchment and involves the complex interaction between the sediment production and transport processes. Consequently, the use of a unique regression equation for the whole range of possible discharges might be unrealistic (Jansson 1996; Zarris and Koutsoyiannis 2005) because it practically denotes the same sediment source for every flow condition that is obviously not the case in wash load conditions.

3 Study Site

Nestos River is one of the major Mediterranean river systems and occupies a total area equal to 6,200 km^2, from which 3,320 km^2 belong to Bulgaria and the rest to Greece. The river length from its sources till the outflow to the North Aegean Sea is equal to 130 km. A small portion of the Bulgarian part of the catchment (area of 188 km^2) that belongs to Dospat River is diverted to Evros River by the Dospat Dam. In the Hellenic part of the catchment two hydroelectric dams have been constructed, namely (from upstream to downstream) the Thisavros and the Platanobrisi Dams equipped with pumped storage facilities. The completion of the dams' construction took place in September 1996 for the first and in October 1997 for the latter. In Fig. 1 a description of the study site is presented. It is clear that the Bulgarian part of the catchment is almost free of dams except the Dospat Dam and Shiroka Polyana Dam in two small tributaries.

Fig. 1 Hydrographic map of the Nestos River catchment

The Nestos R. originates from the eastern slope of Rila Mt and forms a narrow mountainous basin, confined by the Strymon catchment to the west, the Rhodope Mts to the east and the Aegean Sea to the south. After the confluence of Bijala Mesta and Cherna Mesta, the river flows through a rift plain between Mts Pirin and Rhodope, with their 109 small alpine glacial lakes and tarns. The headwater regions contain impressive geomorphologic structures, canyons and steep forested rocky gorges. Acid silicate rocks cover 68% of the basin. Metamorphic formations (gneisses, amphibolites, mica schists and marbles), Quaternary volcanics, with a variety of base and precious metals mineralization and geothermal fields, and granite plutons shape the upper and middle parts.

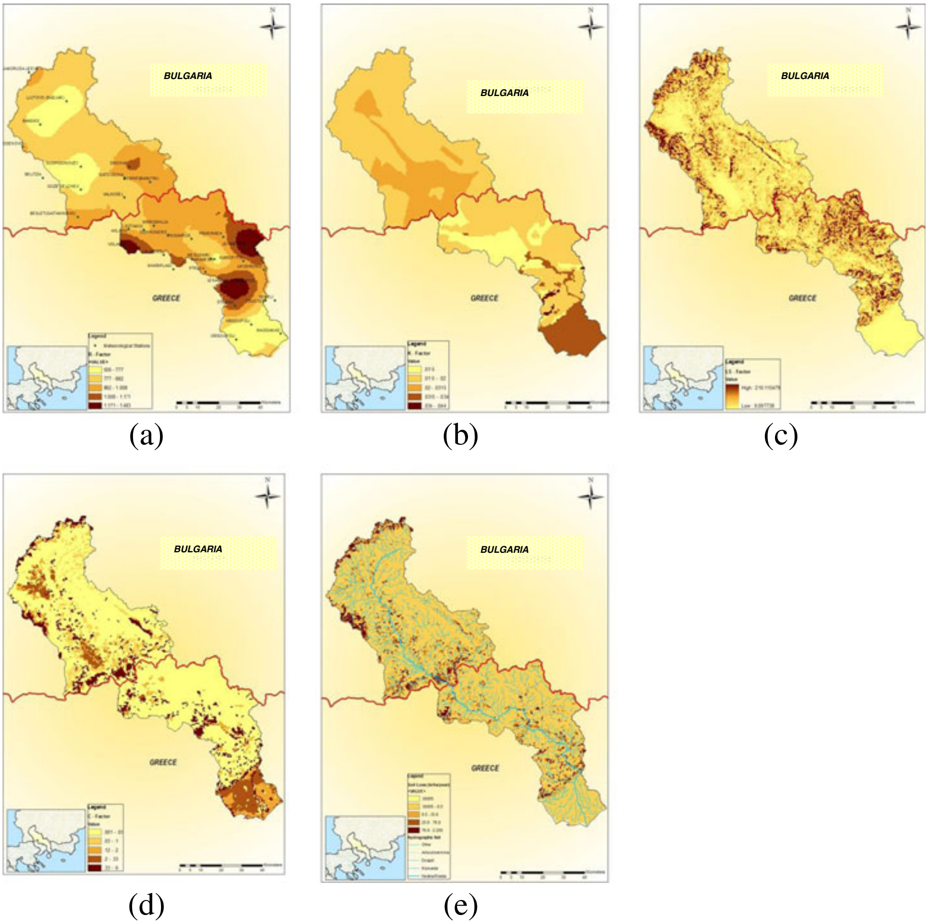
The climatic conditions are typical Mediterranean on the Aegean Sea coast with a dry spell between June and September; while further upstream acquire continental characteristics. Mean catchment elevation is 420 ma.s.l., whereas the corresponding value only for the Bulgarian part is 1,318 m. Mean annual discharge at Temenos gauging station (catchment area 4,954 km^2) is equal to 39·6 $m^3\ s^{-1}$ and the catchment's mean annual precipitation is 680 mm, with the least values found near the river's delta. The expected mean annual sediment load in Thisavros Reservoir is equal to 0.4 hm^3 as determined from the projects' design study (PPC 1979). The geomorphology of the whole catchment may be divided into three different elevation zones. The mountainous zone, with elevations ranging between 600 and 3,000 m, exhibits a very dense and complex hydrographic network that flows through rigid geologic formations (e.g. limestones) with relatively dense vegetation cover. The central zone, with elevations ranging between 200 and 600 m, exhibits a relatively sparse hydrographic network with gentle slopes as well in-stream deposits, and alluvial fans are prominent except from certain segments of the river reach with excessive stream erosion. The coastal zone is almost identical to the river's delta with very mild slopes. Nestos catchment's geology belongs to Rodopi geotectonic zone and consists of metamorphic geologic formations (gneiss, schists with marble intercalations) as well as granite penetrations and volcanic intrusions. Vegetation cover maps for both Greece and Bulgaria from the CORINE classification system were supplied by the European Environment Agency (EEA). Extensive parts of Nestos R. catchment (approximately 65%) are covered by forest lands (especially the upstream parts) followed by irrigated lands (17%), while the remaining 18% of the catchment is covered by diverse vegetation.

Nestos R. is a typical transboundary catchment with Mediterranean type hydrological characteristics where the integration of various technical, environmental, economic and social issues is crucial in order to apply the European Union Water Framework Directive (WFD) in the river catchment, where competing water uses are ever increasing, since Greece has built a series of hydro-power plants and Bulgaria now struggles for rapid economic growth in a market economy. However, the sediment issue is fragmentary addressed and it is for very specific issues only covered by these EU policies and directives. Although it is clear that good environmental status in a water body also requires a good sediment status, more knowledge is required to enable the various linkages between sediment management and WFD objectives to be properly understood. Guidance is needed on how to include sediment management in river basin planning. Short term actions could include the collation of case studies and the preparation of guidance to help sediment managers and river basin managers understand the links between sediment and water, to prepare sediment management plans, and to promote the inclusion of sediment management issues in the second round of River Basin Management Plans (RBMPs) where it is relevant and beneficial to do so. This paper is a substantial contribution towards the fulfilment of this purpose.

As previously stated, soil erosion is calculated by a GIS-based procedure of the USLE approach, where all parameters are represented as raster files (i.e. grids). The *R*-factor is computed from Eq. 2 with α=1.3. However, in the absence of any relative information within the study area, it is assumed that the use of the above relation will not induce significant errors in the computation of soil erosion, although mean annual rainfall rates in the catchment are within the range of the corresponding values for Tuscany, Italy, where this relation was originally developed. The spatial distribution of mean annual rainfall was determined by applying Kriging interpolation procedures on mean annual rainfall values from 35 rainfall stations located in the greater Nestos R. catchment. In order to determine the *K*-factor, soil formations were grouped in five categories according to parental geologic material as digitized from the geologic maps. Values of *K*-factor were assigned to every soil category (van der Knijff et al. 2000) and finally were computed for every grid cell. The *LS*-factor was determined in SEAGIS model by using spatial distribution of a detailed Digital Elevation Model (DEM) with cell size equal to 100 m*100 m. The *C*-factor was assigned to every land use category and eventually to every grid cell using values from the relative literature (e.g. Morgan 2005) and *P*-factor was set equal to unity. Finally, all factors were imported in the GIS environment and soil erosion results were produced by simply multiplying the five different raster data sets. The associated maps of soil erosion and the USLE parameters are presented in Fig. 2.

Sediment discharge data with simultaneous measurements of river discharge for Temenos gauging station were made available from the “Pubic Power Corporation of Greece (PPC)”. Data consists of 114 measurements between the years 1965 to 1983. The suspended sediment discharge sampling is infrequent, since there are long periods with no measurements at all, and the majority of the measurements refer only to low or medium flows. The strategy for the calculation of the catchment’s sediment yield is: (a) construct an appropriate suspended sediment rating curve, and (b) apply the mean daily river discharges to the rating curve to attain the mean daily sediment discharges. Rating curves valid for the period 1965–1983 will not be applied to more recent years as any changes in land uses may be reflected to the rating curve parameters. The time windows of the available data are shown synoptically in Table 1. Mean annual sediment yield is to be calculated for the period 1965–1983 (18 years) when the sediment discharge measurements have been accomplished. Unfortunately, PPC has published only mean monthly discharges for that period unlike during more recent years between 1980 and 1997 (18 years) for which daily values of river discharge were made available. A very simple disaggregation technique has been used to compute mean daily discharges from monthly values based on the proportion of daily to monthly values according to the available daily discharge data for the specified time period. This technique, although simplistic and without any theoretical verification, maintains the proportionality between daily runoff peaks (during which the vast majority of the annual sediment yield is transported) to average monthly flows based on the same period daily values.

The broken line interpolation was introduced by Koutsoyiannis (2000) as a simple alternative to numerical smoothing and interpolating methods and is treated here as a surrogate for the ordinary single rating curve. The main concept is to approximate a smooth curve that may be drawn for the data points with a broken line, which can be numerically estimated by means of a least squares fitting procedure. If the only objective used for fitting the broken line is the minimization of total square error, then the result might be a very rough broken line, depending on the arrangement of the data points. However, the roughness of the broken line can be controlled by introducing as a second objective the minimization of the roughness. The broken line is a concatenation of straight-line segments,



(a) (b) (c)

(d) (e)

Fig. 2 Application of the USLE to the Nestos R. catchment (**a**) R-factor, (**b**) Kfactor, (**c**) LS-factor, (**d**) C-factor, and (**e**) soil erosion map

where the number of the straight-line segments is numerically the outcome of the compromise between the two objectives of minimizing the fitting error and the roughness of the broken line. Considering that the prevailing fluvial form in Nestos R. (near Temenos gauging station) is the gravel-bed form, a broken line with two segments is assumed. In such a fluvial form, there is a distinct threshold discharge for sediment motion, which is attributed to the development of the well-known armor layer. That is, the surface layer visible at low flow is coarser than both the substrate and mean annual bedload transported.

Table 1 Available measurements at Temenos gauging station (Source: PPC)

Period of instantaneous measurements (discharge—sediment discharge)	Number of sediment discharge measurements	Period with published mean daily discharges	Period with published mean monthly discharges
12/1965–02/1983	114	01/1980–05/1997	10/1965–05/1997

It has often been assumed that this armor is “washed out,” or at least strongly subdued, during flood flows. But it is precisely in the middle of flood flows when it is impossible to verify this hypothesis. It can be assumed, however, that below this discharge threshold there is no exchange of the armored suspended sediment with the riverbed. Once the surface, coarse material, armor layer fully breaks up beyond the threshold discharge and exposes a larger range of particle sizes underneath, the transport rate significantly increases. Additionally, bank erosion during high discharges will enhance the sediment availability in the river bed. After several trials in a trial-and-error procedure it is concluded that the threshold discharge that minimizes the error function is 31 m^3/s, which is less than the mean average flow in Temenos gauging station. That means that the breaking up of the armor layer is a quite frequent event. Therefore, it may be concluded that frequent runoff events are relatively more important to the long-term yield than catastrophic flooding events; most of the long-term average load is transported by events with not excessive return periods. The validity of the broken line rating curve was evaluated in the case of the Acheloos River in Western Greece, which is a typical perennial gravel-bed river. In this case, mean annual sediment yield was measured by means of a comprehensive hydrographic survey of the reservoir (Zarris et al. 2002) resulting in the estimation of the total mass and spatial distribution of the sediment deposits. The measurement of the mass of the accumulated sediments in Kremasta reservoir was used to validate the applicability of a number of different sediment rating curve formulations for the Acheloos R. at *Avlaki* gauging station just upstream of the reservoir. It is shown that, among a number of different representations of the relation between river and sediment discharge, the broken line interpolation procedure is the only one that can reproduce with relative accuracy the mass of the deposited sediments in the reservoir. All the other rating curves formulations examined were by far unsuccessful on reproducing the cumulative sediment mass in the reservoir. The main reason is that the broken line interpolation is not a typical statistical tool, but it can reproduce the complex mechanism of—in stream—erosion and deposition with varying discharge (Zarris and Koutsoyiannis 2005).

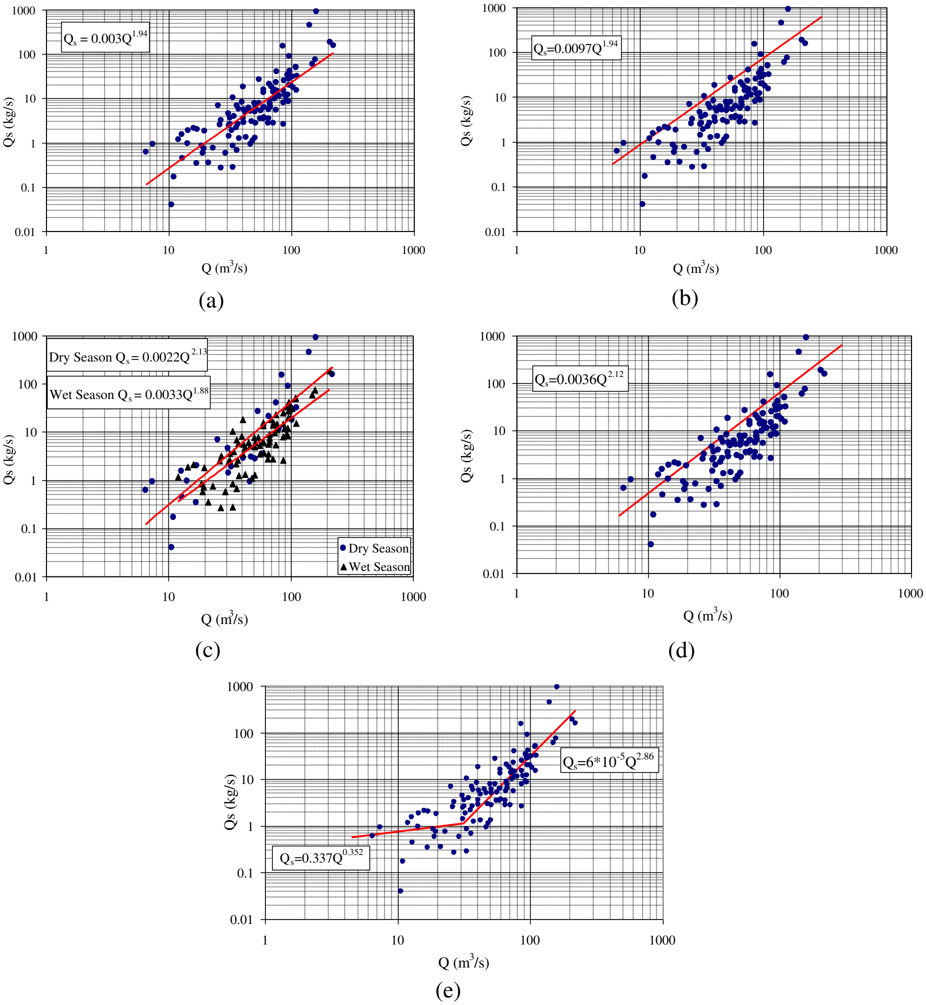
4 Discussion and Conclusions

The mean annual soil erosion from the USLE application with SEAGIS software for the whole catchment is equal to 1,080 $\mathrm{t km^{-2}}$. The values associated with the Bulgarian and the Hellenic parts of the catchment are equal to 1,257 and 852 $\mathrm{t km^{-2}}$ respectively. Sediment yield is computed after constructing five different types of rating curves, namely (a) the simple power form for the whole range of measured discharges, (b) same as previously but with the Ferguson correction, (c) different curves for the wet—dry season of the year, (d) the nonlinear regression, and (e) the broken line interpolation. Table 2 presents the rating parameters for each type of rating curves. Figure 3 presents the rating curves (a) to (e) in a log-log plot so they are illustrated as a straight line.

It is evident that at high discharges the simple rating curve (a) significantly underestimates high sediment discharges and the regression tends to be highly heteroscedastic. This is a major drawback of this method. The Ferguson correction leads to a better fit at high discharges but obviously overestimates the lower and middle intervals of suspended sediment discharge measurements. The reason is that the Ferguson correction factor has a quite high value ($E(\eta)=2.94$) because the standard deviation of the log-linear regression error term is also a significant value due to the obvious scatter of the data points. The correction factor is directly multiplied with the rating parameter, *a,* causing a shift of

Table 2 Values of rating parameters for each type of rating curves

	Linear regression of log-transformed quantities	Linear regression with Ferguson correction	Linear regression—seasonal curves		Non linear regression	Broken line interpolation	
			Dry season	Wet season		<31 m^3/s	>31 m^3/s
Rating parameter, *a*	0.003	0.0097	0.0022	0.0033	0.0036	0.337	$6*10^{-5}$
Rating exponent, *b*	1.94	1.94	2.13	1.88	2.12	0.352	2.86



(a) (b) (c) (d) (e)

Fig. 3 Forms of different rating curves at Temenos gauging station: **a** simple rating curve, **b** Ferguson correction to simple rating curve, **c** simple rating curves to the dry and wet seasons, **d** nonlinear regression, and **e** broken line interpolation the rating curve towards larger sediment discharge values at all discharge classes. Nonlinear regression is a powerful technique facilitated by the significant increase of computer power. The major shortcoming of this method is that, because of the aim to minimize the fitting error, it fits best only to the pairs of high sediment and river discharges leading to an overestimation for the medium and low pairs of measurements. The broken line interpolation, on the other hand, is homoscedastic and the inflection point is determined by a trial-and-error procedure seeking the minimization of the error function (Koutsoyiannis 2000).

Results of sediment yield for all types of rating curves are presented in Table 3. Apart of the simple rating curve which yields the least value of sediment yield (as expected), all other values are quite close to each other, with the broken line yielding the highest value. This value is treated as the correct one for the Nestos R. catchment's sediment yield in the light of the findings in Acheloos R., as stated earlier in the text. Therefore, the mean annual suspended sediment yield for the Nestos R. catchment up to the Greek-Bulgarian borders is computed equal to 203.4 t/km^2. Hrissanthou (2002) applied two different erosion models to that part of the Nestos R. catchment which lies downstream of the dams mentioned above with an area equal to 838 km^2. The two different models gave almost identical results and the estimated mean annual sediment yield for this part of the catchment is equal to 376.5 t/km^2.

Accordingly, mean annual sediment load to Thisavros Reservoir will be 0.7 hm^3 that is almost twice than the expected value from the design study of the reservoir, assuming the same dry bulk density of the deposited sediments. Sediment delivery ratios (SDR) (i.e. the percentage of soil erosion that leaves the catchment as sediment yield) vary between 11 and 19% ignoring the least value from the ordinary rating curve formulation (SDR=6%). These values are in good correspondence with associated values reported in the related literature by various researchers who attempted to correlate observed SDR values mainly with catchment area. For instance, Renfro (1972) developed an equation relating SDR with the drainage area observed in 14 watersheds in the Blackland Prairie Area in Texas, USA. The model shows a good relationship between SDR and the drainage area (R^2=0.92). The model can be written as follows:

$$\log SDR = 1.7935 - 0.14191 \log A \tag{4}$$

where A is the catchment area in km^2. Vanoni (1975) used the data from 300 watersheds throughout the world to develop a model by the power function. This model is considered a more generalized one to estimate SDR and has the form of the equation:

$$SDR = 0.42A^{-0.125} \tag{5}$$

Table 3 Sediment yield estimates for each rating curve

	Linear regression of log-transformed quantities	Linear regression with Ferguson correction	Linear regression—seasonal curves	Non linear regression	Broken line interpolation
Mean annual sediment discharge (kg s^{-1})	9.5	28.0	17.9	28.8	31.9
Mean annual sediment yield (t km^{-2})	60.7	178.5	114.6	183.7	203.4
Sediment delivery ratio	0.06	0.17	0.11	0.17	0.19

where A is the catchment area in square miles. The USDA SCS (1979) developed a SDR model based on the data from the Blackland Prairie, Texas. A power function with catchment area is derived and has the form of the equation:

$$SDR = 0.51A^{-0.11} \tag{6}$$

where A is the catchment area in square miles. The values of SDR of the Nestos R. catchment resulted from these equations (A=4,954 km^2) are equal to 18.6%, 16.3% and 22.2%, respectively that are very close to the estimates given in this paper. Moreover the SDR value as computed from the broken line interpolation procedure seems to be the one that corresponds better with these three estimates from the above equations. Therefore, there is strong evidence that the soil erosion and sediment yield estimates for the Nestos R. catchment are concise and in good agreement with the general trend of global sediment yield estimates.

Table 4 presents a comparison between estimations of the Nestos R. sediment yield from six other references. It is shown that all sediment yield estimates are within the same order of magnitude, while the estimation of this study acquires the highest value of sediment yield for almost the maximum catchment area. It is evident, however, that different techniques and data were applied from all the researchers in computing sediment yield, because there is a clear inconsistency between sediment yield and catchment area. The correlation coefficient between sediment yield and catchment area is equal to −0.39 which indicates a rather weak correlation. The minus sign of the correlation coefficient dictates that sediment yield decreases as catchment area increases. Conclusively, it can be stated that a certain sediment yield value for Nestos R. for all catchment scales, according to the published data, cannot be hypothesized with a satisfactory degree of confidence. Moreover, it is shown that even for a single river catchment there are a number of sediment yield estimates that presumably do not coincide well. Therefore, it is important for those researchers, who are attempting to develop empirical relations between sediment yield and certain geomorphologic and/or hydrologic variables with published data from the related literature, to carefully select and evaluate the sediment yield data that are employed into their correlation analyses.

Nearby catchments that discharge into North Aegean Sea also acquire similar values of sediment yield. These catchments are from West to East (Fig. 4): (a) Aliakmonas R., (b)

Table 4 Comparison of mean annual sediment yield rates for Nestos R. with related references

Reference	Gauging station/ catchment area (km^2)	Mean annual sediment discharge (kg/s)	Mean annual sediment yield (t/km^2)
Gergov (1996) & Andredaki et al. (2008)	M. Kula (Bulgaria)/1511	9.7	202
Paraskevopoulos-Georgiadis (2001)	Greek-Bulgarian Border/3584	20.6	181.0
Paraskevopoulos-Georgiadis (2001)	River Mouth (Greece)/6265	15.5	78.0
Gergov and Karagiozova (2002)	Hadgidumovo (Bulgaria)/2123	8.5	125.0
UNEP/MAP (2003)	River Mouth (Greece)/6100	30.9	160.0
Poulos and Alexandrakis (2005)	Temenos (Greece)/4394	21.9	157.4
This study (2011)	Temenos (Greece)/4954	31.9	203.4

Fig. 4 Map of the main rivers discharging to North Aegean Sea

Axios R., (c) Strymonas R., and (d) Evros R. Psilovikos and Margoni (2009) published that in the Strymonas R. catchment the mean annual suspended sediment yield is equal to 369.2 t/km^2, as measured from fluvial deposits in Lake Kerkini. Zarris et al. (2006) reported that in the Aliakmonas R. catchment mean annual suspended sediment yield is computed equal to 415 t/km^2 for the most downstream sediment gauging station. Poulos (1997) for Evros R. stated that the corresponding value is around 310 t/km^2. The only value that is outside of the general trend is the one for Axios R. reported by UNEP/MAP (2003) with reported value around 1,220 t/km^2. All references are presented in Table 5.

However, the divide in sediment yield values can be quite abrupt. Zarris et al. (2006) published mean annual sediment yield values from 14 catchments in North Western Greece with areas between 200 and 1,700 km^2. Sediment yield values range between 280 and 2,200 tkm^{-2}, which are significantly higher than Nestos R. corresponding value. This is

Table 5 Sediment yield of rivers draining in the North Aegean Sea

Reference	Gauging station/ catchment area (km^2)	Mean annual sediment discharge (kg/s)	Mean annual sediment yield (t/km^2)
Aliakmonas R./Zarris et al. (2006)	M. Ilarionas (Greece)/5005	65.8	414.6
Axios R./UNEP/MAP (2003)	River Mouth (Greece)/24497	947.7	1220.0
Evros R./Poulos (1997)	n. Adrianoupolis (Greece)/27465	269.8	309.8
Strymon R./Psilovikos and Margoni (2009)	Lake Kerkini (Greece)/11600	135.8	369.2
Nestos R./This study (2010)	Temenos (Greece)/4954	31.9	203.4

mainly attributed to the fact that in North Western Greece mean annual precipitation is generally more than 1,000 mm and vast areas of the catchments are comprised from flyschs (easily erodible geologic formations) with less dense vegetation cover.

This paper illustrated that both soil erosion estimates from the USLE and sediment yield from the suspended sediment rating curves can provide with quite consistent estimates and can form a good basis at least for a preliminary investigation of a catchment's mean annual sediment yield. The novel approach in this paper is that as much as 5 different rating curves' formulations were implemented in the computation of the Nestos R. suspended sediment yield that employ different statistical techniques and theoretical backgrounds. The ordinary rating curve, that is the outcome of the linear regression of the log-transformed variables, significantly underestimates sediment loads and its application must be avoided in all instances. Especially in gravel-bed rivers, it is recommended that the broken line interpolation must be employed taking into consideration the arrangement of the simultaneous measurements of river and suspended sediment discharge. Finally, it was shown that the single use of the suspended sediments rating curves (if formulated correctly) even with inadequate data is still a quite realistic and reliable method for estimating a large catchment's sediment yield even in Mediterranean type catchments. It is necessary to treat the simultaneous measurements of river and suspended sediment discharges not like simple points in a graph for a strict statistical line fitting, but to explore the valuable information that is hidden behind these data.

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