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Modeling hydromorphological processes in a mountainous basin using a composite mathematical model and ArcSWAT

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ABSTRACT

Hydromorphology is a matter of water and sediment. This constitutes the study of hydrological processes, as well as of the soil and streambed erosion processes imperative. This study presents two different models aiming at continuous simulations of hydromorphological processes at the basin scale. The first model is a Composite Mathematical Model (CMM), consisting of three submodels: a rainfall-runoff submodel, a soil erosion submodel and a stream sediment transport submodel. The second model is the GIS version of the Soil and Water Assessment Tool, SWAT. The application of both models results to continuous hydrographs and sediment graphs at the basin outlet. The computed stream discharge and sediment discharge values are compared with field measurements and both models are evaluated, as to their competence of simulating the hydromorphological processes in a basin. The novelty of this research primarily lies in the fact that different ways for producing continuous sediment graphs, are presented. This can be achieved at any stream segment and provides a continuous assessment of the sediment discharge. Additionally, the application of all models is performed at an hourly time step, for long periods of time. This imparts high precision and detail to the hydromorphological study of a basin at the temporal scale. Sediment discharge is a highly nonlinear physical procedure and high levels of disaggregation (subdaily to hourly time steps) incorporate a very high degree of nonlinearity, especially in flooding periods. In this respect, this research highlights the importance of calculating sediment discharge at fine time scales and offers different methodologies to achieve it. Several statistic efficiency criteria were used to evaluate the models' efficiency to simulate the aforementioned processes. As far as the evaluation of CMM is concerned, values for Nash-Sutcliffe Efficiency (NSE), determination coefficient (r^2) and Percent BIAS (PBIAS) amount to 0.974, 0.985 and −10.344, respectively, for water discharge, and 0.647, 0.660 and 12.371, for sediment discharge, whilst regarding the evaluation of SWAT the corresponding values for NSE, r^2 and PBIAS are 0.978, 0.981 and −5.104, for water discharge, and 0.593, 0.664 and −37.155, for sediment discharge. It is considered that the efficiency criteria provide satisfying results.

1. Introduction

Surface runoff, baseflow, stream discharge, soil erosion and sediment transport constitute the basic interrelated natural processes, which perpetually chisel the hydromorphological profile of a basin. The monitoring, analysis and quantification of the aforementioned processes are the key factors for an integrated research at the basin scale. Flood, erosion and sedimentation hazard management and water resource, land use, reservoir and irrigation planning, along with water quality control are only few of the many examples.

Stream discharge is a crucial parameter for quantifying the water cycle, its fluxes and its stocks at different scales. These scales range from a local scale for management of water resources to a global scale for monitoring the climate change (Negrel et al., 2011). Rivers can be beneficial and harmful, in equal measures, for crops, infrastructures and humans. Additionally, they transport and cycle essential nutrients, they filter the water and they are a vital element for the various ecosystems within the basin. Depending on their discharge volume, riverine systems can contribute to either the conservation or the decline of the natural habitats of both the aquatic and riparian life. Continuous hydrologic modeling provides sufficient information on river and stream "behavior", and helps in taking appropriate action, when prompted.

A river, in effect, can be considered a body of flowing sediments as much as one of flowing water (McCully, 1996). The - as possible - accurate estimation of sediment discharge, as a result of soil erosion and sediment transport, is essential for a variety of reasons. Erosion and

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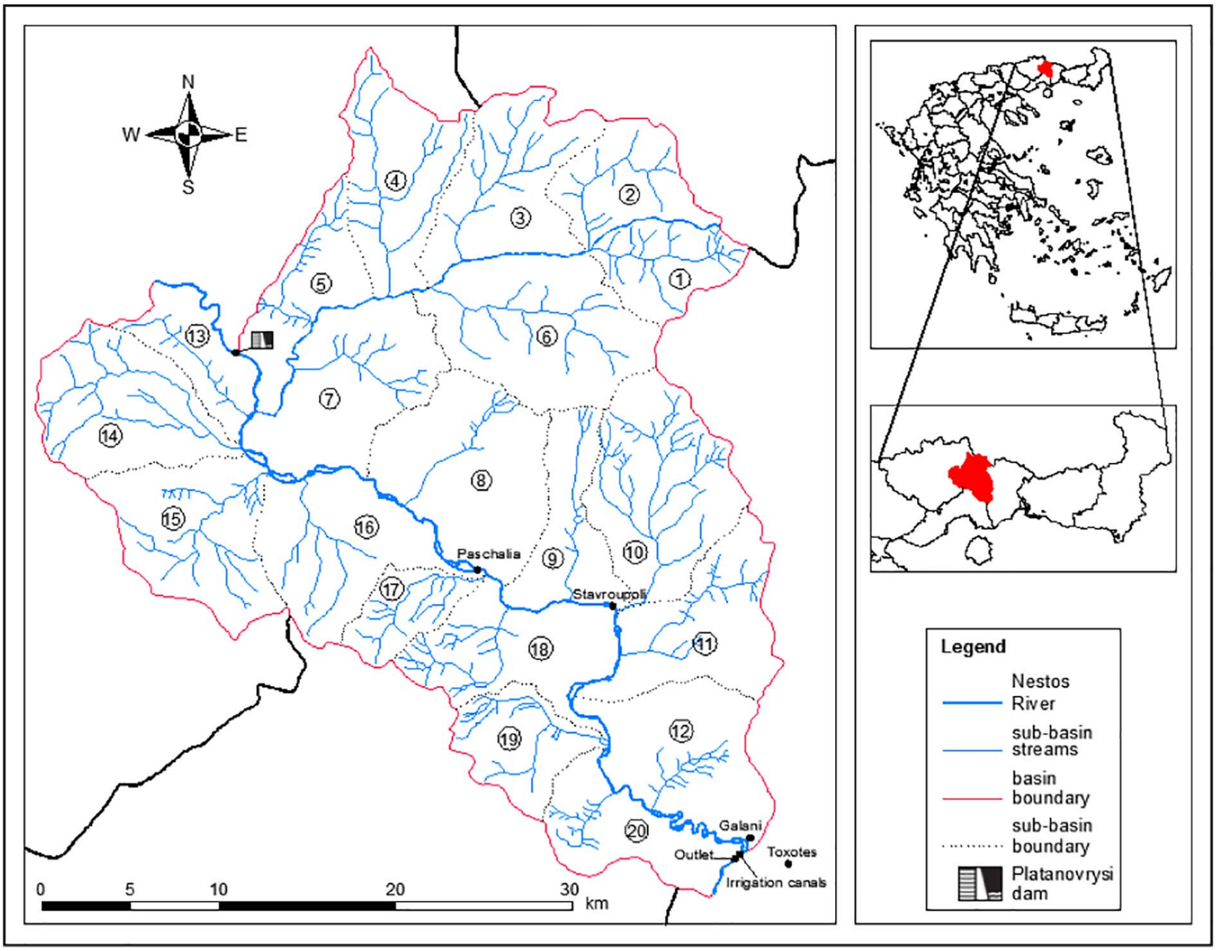

Fig. 1. Nestos River basin downstream of Platanovrysi dam.

deposition influence the wet cross sectional area, whilst excessive deposition can cause problems in navigation and increase of flood events. High concentrations of sediment can cause water temperatures to rise, which, in turn, results in a decline of the dissolved oxygen's levels, with devastating aftermath for aquatic life. Excessive sedimentation can also harm aquatic life, by ravaging its natural habitats. Furthermore, sediments are carriers of nutritional as much as contaminant factors. Additionally, sediments constitute - even today - the most severe complication associated with dams. This is due to the gradual, and in some cases excessive, sedimentation, which leads to a considerable storage loss. Moreover, when hydroelectric structures are present, sediments cause further problems by abrading the turbines. Consequently, the estimation of the incoming sediment load is essential in order to ascertain the viability of dams and find workarounds in case of excessive sedimentation.

The primary step in decision making for flood hazard management, water resource and land use planning and erosion and sedimentation hazards is the monitoring of discharge and sediment discharge. However, monitoring discharge and, even more, sediment discharge is expensive and labor intensive (Emdad, 2004). Hence, the development and validation of models that can efficiently simulate the hydro-morphological processes, is essential.

In this study, hydrologic, as well as soil erosion and stream sediment transport processes are performed at a continuous time scale. The simulations take place in the mountainous Greek part of Nestos River basin (Macedonia-Thrace border, northeastern Greece). The characteristic of the basin is the presence of a dam at its northwestern boundary, which largely affects the discharge, as well as the sediment transport in Nestos River. Along with this, two irrigation canals slightly upstream of the basin outlet (Egnatia bridge of Nestos River) are culpable of a recession of water, during the irrigation period, disrupting the final discharge at the basin outlet.

ArcSWAT and a Composite Mathematical Model (CMM) (Kaffas and Hrissanthou, 2015) are applied to Nestos River basin. CMM consists of three submodels. HEC-HMS 4.0 is used as the rainfall-runoff submodel, by means of which the surface runoff, the baseflow and the total streamflow in the sub-basins are computed. HEC-HMS is a deterministic distributed hydrologic model, which means that it is suitable for hydrologic simulations in dendritic watersheds. The splash erosion model of Poesen (1985), combined with the relationships of Nielsen et al. (1986) and Engelund and Hansen (1967), is used for the estimate of soil erosion in a sub-basin, whilst the sediment routing in the main streams of the sub-basins is achieved by the relationships of Yang and Stall (1976). All simulations take place at hourly time steps, for long periods of time. Some might say that modeling of hourly sediment discharges is somehow the "holy grail" of current research of soil erosion and sediment yield modeling.

Whilst water discharge is frequently simulated continuously and in fine time steps, sediment discharge originating from soil and streambed erosion, is mainly studied as temporally lumped size (monthly, annual etc.).

HEC-HMS, for instance, has been applied for continuous simulations of water discharge in a variety of cases. Boyogueno et al. (2012) used HEC-HMS to compare the computed hydrograph with the corresponding measured one for a four month period, in Sanaga basin in Cameroon. The computed hydrograph approximated reality satisfactorily with a Nash-Sutcliffe Efficiency value of 0.862. Wallner et al. (2012) focus on long-term continuous hydrological modeling - with