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Models for sediment yield in mountainous Greek catchments

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ABSTRACT

In this study we explore the controls over suspended sediment yield in 11 stations situated along six major rivers of Western – Northern Greece (Arachthos, Achelooos, Evinos, Aoos, Kalamas and Aliakmon). Values of area specific sediment yield for these stations come from reanalysis of existing records, by adaptation of the broken rating curve concept, and range from 140 to 2300 t km^{-2} y^{-1}. We investigate the correlations among suspended sediment yield values and many geomorphic - topographic, morphometric, textural, tectonic, geological-lithological and climatic (precipitation-runoff) characteristics of the corresponding basins, along with land cover variables and RUSLE factors (LS, R, K and C RUSLE), from maps of the European Soil Data Center. We find the principal controls to be slope and lithology followed by precipitation, runoff and landslide frequency. Factors such as ground cover (percentage of barren land within the basin) and alluviation of the river, have also some relevance. With the use of stepwise multiple regression analysis we build a model that employs three variables: slope (in percent), precipitation (mean annual, in mm) and lithology (as percentage of the easily erodible geological formations within the catchment), where the contribution of lithology is an additive term to the slope-precipitation power relationship. The proposed model achieves good statistics (NSE = 0.84). From the other models tested with our data set BQART performs well while RUSLE2015 of the ESDC performs poorly.

1. Introduction

Sediment discharge can be defined as the quantity (usually measured in M/T) of the eroded material transported to a certain location in the fluvial system, over a specified time period; while sediment yield is the accumulated, over a time period, usually annual, sediment discharge per unit area of the upstream catchment, commonly expressed as t km^{-2} (Gregory and Walling, 1973). Of the two components of sediment load, particulate and dissolved material, the first is generally considered to be much larger than the second, even though the contribution of dissolved material appears significant in large basins dominated by periglacial processes (Anderson and Anderson, 2010). Particulate load is distinguished into suspended load and bedload, a distinction more *fuzzy* as it largely depends on flow properties. Nevertheless, bedload is considered a small fraction (~10–15%) of the whole particulate load (UNESCO, 1985), except in semiarid environments and/or gravel bed rivers where it constitutes a much larger fraction (Reid, 2002; Yasi and Hamzepouri, 2008).

Several attempts have been made to propose a predictive model of SSY (suspended sediment yield) that will hold true in particular areas of the Mediterranean basin. Verstraeten et al. (2003), studying 22 reservoir basins in Spain, developed a scoring model (factorial scoring model – FSM) that employed five factors: slopes, gullies, land cover, lithology, and shape of the catchment. Those five factors were to be assessed in situ, their scores (1–3) multiplied and then added to a term depending only on the area of the basin, plus a constant. Notably, the entire basin was not to be characterized and assigned a score, but only those parts near the outlet and in a buffer around the principal drainage network. This model, that belongs to the scoring models family along with PSIAC (PSIAC, 1968), but also with the USLE formula, was later tested and applied in Italy by de Vente (2009) with some modifications. In this approach, landslides were recognized as an important factor and no-area variations (lacking the area term) of the FSM were developed, and factors were also weighted. The application of the model was found to be successful in Spain ($R^2 = 0.78$, $n = 22$) and somehow less successful in Italy ($R^2 = 0.67$, $n = 28$, no-area model with a landslide factor). Apart from FS models, a lot of multiple regression models for regional use have been developed worldwide, of which de Vente (2009) presented an extensive list.

Logically, we do not expect the area to have some kind of influence on the sediment yield. What we do expect is that it influences sediment delivery ratios (Walling, 1983; de Vente et al., 2007). Aalto et al. (2006) claimed that 'the observed statistical relationships (between area and sediment yield) are likely to be artifacts of the ratio between sediment-producing area and depositional area (or length), which

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generally decreases with increasing basin size'. If this is true, the inclusion of an area term in a model reduces its explanatory merit, except when used as a proxy for sediment delivery ratio.

Another *paradox* in these models is the absence of the precipitation in some form or index. Even though the authors included several precipitation indices in their study, a clear causal relationship was not found. Maybe this is owing to the small precipitation amounts and gradients within the areas of the case studies (350–700 mm) or to the use of global grid data (CRU, Global Climate Dataset) that usually tend to smoothen the precipitation gradients. Another, probable, reason is that precipitation is not a major control of SSY in these particular areas.

Indeed, the influence of precipitation has been an issue of controversy among various researchers. For example, in the above-mentioned study of Aalto et al. (2006) in the Bolivian Alps, of 45 purely erosional catchments (that is, catchments largely free of significant sediment sinks) precipitation and runoff do not present significant relationships with sediment yield. In this highly tectonically active and climatically intense setting, where large amounts and gradients of precipitation do exist, authors are challenged to provide possible explanations for this finding as, for instance, the assumption of steady-state rates between river incision and hillslope mass wasting that are in long-term topographic equilibrium (Montgomery and Brandon, 2002). The authors recognized the prevailing influence of topography (slope, relief, elevations) and presented the influence of geology by drawing semiparallel trendlines in slope – SSY and runoff - SSY scatterplots, each line representing a distinct lithological background.

In another tectonically active geographical setting, New Zealand, the relative importance of geology and precipitation has been long debated between researchers (Hicks et al., 1996). The extensive operational monitoring network and the abundance of high-quality data, the broad range of the conditions and their systematic work, has allowed scientists from New Zealand to resolve the controversy by proposing a model that recognizes different clusters of basins, according to the principal physical processes that govern the sediment production in each basin. In this model, WANSY2, covering the region of Waikato-Auckland-Northland, the structure implies that precipitation is the prevailing factor for catchments dominated by resistant (*hard*) lithologies; while in catchments consisting of less-resistant (*soft*) lithologies, slope is the prevailing factor (Haddadchi and Hicks, 2016).

Another category is the global sediment yield models, pooling data from inventories of thousands of stations worldwide (Milliman and Meade, 1983; Milliman and Syvitski, 1992; Hovius, 1998; Ludwig and Probst, 1998; Beusen et al., 2005). Perhaps the most comprehensive representative of these models is the BQART model of Syvitski and Milliman (2007). This model, applied to a database of 488 rivers, accounted for 96% of the between river variation in the long term (± 30 years) sediment yield. An important characteristic of the BQART model, in relation with previous versions, is that it allows for the inclusion of factors such as human disturbances on, and trapping efficiency of, the basins. It also allows for the consideration of their lithological and glacial character. Human disturbances, which are now quite pronounced on the majority of large to medium rivers of the world (Meybeck, 2003; Syvitski et al., 2005), are represented in the model by the combination of two common indices such as GDP per capita and population density for the area of the basin.

For the Mediterranean environment, as reviewed broadly and comprehensively by J.C. Woodward (1995), the main controls on the sediment production are found to be topography (mainly slope of the valley sides), precipitation and precipitation intensity, the lithology of the basins, and the land use-land cover conditions. More specifically, the geology and landforms of our study area, northwestern Greece, is treated thoroughly in this review, with a particular view for badlands.

In Greece, measurements of suspended sediment loads were performed only by the Public Power Corporation in stations situated mostly along rivers of the western and northern parts of the country and for periods not exceeding 15–20 years. Zarris et al. (2006) published values for 11 stations in 6 river catchments, based on reanalysis of the existing records by adaptation of the broken rating curve concept. In this methodology, the rating curve is supposed to break in around the bankfull discharge, attaining a steeper slope for larger discharges (Koutsoyiannis, 2000; Zarris and Koutsoyiannis, 2005). This is attributed to the destruction of the armored layer in alluvial rivers during floods. Zarris et al. (2007) made an attempt to study the correlations between sediment yield and morphometric and hydrological (runoff) indices of the catchments. No other correlation was found, except a very strong one between sediment yield and the mean annual flood ($r = 0.91$). This is consistent with the frequency–magnitude aspect of the phenomenon: few major floods carry the bulk of the load (Meade and Parker, 1984; Mulder et al., 1998; Meade et al., 1990) and a few days can sometimes carry the loads of tenths of years. Brown and Ritter (1971) reported the case of Eel River, a river draining the steep-sloped coastal mountains of California, where 3 days in 1964 delivered more sediment than had been carried in the previous 8 years combined.

Previous modeling efforts in Greece have recognized rainfall and lithology as main controls of sediment productivity (Koutsoyiannis and Tarla, 1987). Other authors, mainly concerned with delta progradation, have identified slope (relief) and (elongated) shape of the catchments as main controls (Karymbalis et al., 2001); while Poulos et al. (1996) proposed a power relation of annual sediment flux with the area of the basin.

The aim of this study is to explore the controlling factors of soil erosion and sediment yield in the mountainous catchments of northwestern Greece and to develop an empirical multiple regression model that can be used for predictive purposes. Ideally, this model should be kept simple, utilizing readily available and, also, unambiguous data.

2. Study area

The catchments of the western part of the Greek peninsula that drain into the Ionian Sea are known to be the most prone to erosion and soil loss as well as highly productive in terms of sediment discharge among the Mediterranean catchments (Fig. 1). Drainage basins in Albania and western Greece rank in a first place, with sediment yields attaining values over 2000 t km^{-2} y^{-1} and sometimes reaching as much as >4000 t km^{-2} y^{-1} (Woodward, 1995; Poulos et al., 1996). The combination of steep slopes, a rugged, tectonically active terrain, and heavy seasonal precipitation is probably responsible for these high values. Actually, this area is the most tectonically active in the Mediterranean region caused by the subduction of the African plate beneath Eurasia with rates of uplift and subsidence up to 100 m in historical times (Bailey et al., 1993).

The Pindus Mountains and much of the Epirus region are a distal segment of the Alpine Mountain system that stretches through central and southern Europe (Everett et al., 1986). The compressional tectonics of Epirus have resulted in a series of overlapping lithofacies belts that trend NNW-SSE at right angles to the general direction of compression and parallel to the present Ionian coastline (Woodward, 1990). Increased deposition of clastic siliceous *flysch* sediments took place by the late Eocene, after the initiation of the Pindus Thrust, reflecting a change in the position of Greece from oceanic to continental margin (King et al., 1997). The flysch strata are turbidite deposits of mudstone, siltstone, and sandstone, whose great thickness reflects the enormous input of sediments from the newly uplifted mountains (Richter et al., 1978).

This major period of flysch sedimentation at the end of the Eocene, and over the Hellenides, continued no later than the early Miocene, when the onset of major tectogenesis uplifted the flysch above base level to the point that it now uncorformably overlies the limestone strata (Richter et al., 1978; Clews, 1989). The late Cenozoic uplift of the flysch also explains the general instability of the flysch lithology in the Epirus region, which shows many signs of intense erosion in headwater flysch basins (Hamlin, 2000). Dissection of erodible flysch