Science of the Total Environment 619–620 (2018) 672–684

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Modelling spatial and temporal variations of annual suspended sediment yields from small agricultural catchments

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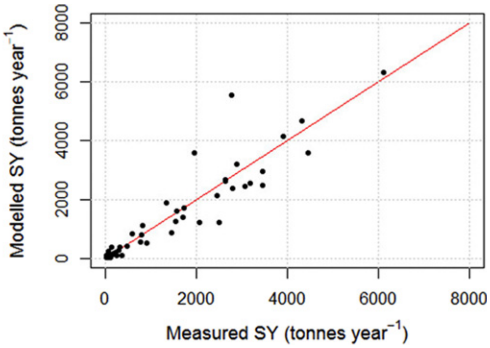
HIGHLIGHTS

- Catchment and hydrological variables were used in sediment yield regression models.
- Year-specific flow variables could explain year-to-year sediment yield variations.
- Sediment yield data for Irish catchments was compiled and reviewed.
- Complex relation between catchment size and area-specific sediment yield was found.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 11 July 2017
Received in revised form 13 October 2017
Accepted 14 October 2017
Available online xxxx

Editor: Dr Ouyang Wei

Keywords:
Sediment yield
Empirical sediment model
Spatial and temporal variation
Ireland
Sediment yield-catchment area relationship

ABSTRACT

Estimates of sediment yield are important for ecological and geomorphological assessment of fluvial systems and for assessment of soil erosion within a catchment. Many regulatory frameworks, such as the Convention for the Protection of the Marine Environment of the North-East Atlantic, derived from the Oslo and Paris Commissions (OSPAR) require reporting of annual sediment fluxes. While they may be measured in large rivers, sediment flux is rarely measured in smaller rivers. Measurements of sediment transport at a national scale can be also challenging and therefore, sediment yield models are often utilised by water resource managers for the predictions of sediment yields in the ungauged catchments. Regression based models, calibrated to field measurements, can offer an advantage over complex and computational models due to their simplicity, easy access to input data and due to the additional insights into factors controlling sediment export in the study sites. While traditionally calibrated to long-term average values of sediment yields such predictions cannot represent temporal variations. This study addresses this issue in a novel way by taking account of the variation from year to year in hydrological variables in the developed models (using annual mean runoff, annual mean flow, flows exceeded in five percentage of the time (Q5) and seasonal rainfall estimated separately for each year of observations). Other parameters included in the models represent spatial differences influenced by factors such as soil properties (% poorly

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https://doi.org/10.1016/j.scitotenv.2017.10.134

drained soils and % peaty soils), land-use (% pasture or % arable lands), channel slope (S1085) and drainage network properties (drainage density). Catchment descriptors together with year-specific hydrological variables can explain both spatial differences and inter-annual variability of suspended sediment yields. The methodology is demonstrated by deriving equations from Irish data-sets (compiled in this study) with the best model efficiency of 0.84 and best model fit of adjusted R^2 of 0.82. Presented approach shows the potential for regression based models to model contemporary suspended sediment yields in small river systems.

1. Introduction

On land, soil erosion and associated loss of nutrients and organic matter from catchments reduce soil productivity and biodiversity, thereby adversely impacting soil ecosystem services (Crosson, 1997; Gregory et al., 2015; Lal, 2014). Increased levels of fine sediments delivered to fluvial systems can harm aquatic life both (i) when in suspension, and also (ii) when it is deposited on the stream-bed where its impact on ecological habitats can be particularly severe (Bilotta and Brazier, 2008; Jones et al., 2012; Kemp et al., 2011; Owens et al., 2001; Sear et al., 2016). Sediment is therefore an important factor threatening compliance with the water quality and ecological requirements of the Water Framework Directive (WFD; 2000/60/EC) in many countries and is a threat to many endangered aquatic species both in freshwaters and in the oceans. In addition, concern for aquatic life in the North-East Atlantic has led to the OSPAR Convention and mandatory reporting of annual sediment export to this ocean.

While there are no specific guidelines for sediment standards in the WFD, assessment of national sediment yields (expressed as either in the absolute terms (SY, t y^{-1}) or as area-specific sediment yields (SSY, t km^{-2} y^{-1})) could contribute to the development of informed sediment targets for the protection of freshwater systems. For example, in the UK, sediment regime targets and thresholds for triggering investigations were proposed based on lower and upper quartiles of SSY data from over 100 SSY measurements and catchment characteristics (Cooper et al., 2008). In the USA, on the other hand, section 303(d) of the Clean Water Act developed a catchment specific Total Maximum Daily Loads (TMDL) approach for impaired waters for pollutants, including sediment, as a basis for quality assessments (e.g. Borah et al., 2006; Keyes and Radcliffe, 2002; Mishra and Deng, 2009). Direct measurements of sediment flux are however extremely challenging at a national scale due to the substantial human and financial resources required. Therefore, an alternative approach (supported by sediment yield models) is required to estimate sediment flux that can extend the scope of sediment export estimation to unmonitored catchments. Regression equations derived from catchment characteristics and climatic conditions can be used for such predictions. The main advantage of this type of approach over spatially distributed process-based soil erosion/river transport models are smaller data requirements, reduced complexity, ease of use but also relative accuracy (Merritt et al., 2003). In addition, the regression analysis itself can provide additional understanding of the factors influencing sediment levels in the study region.

2. Background

Although the most commonly used prediction variable for SSY is catchment area (A), attempts to model annual sediment yield using catchment area as the only predictor variable are generally unsatisfactory due to a high scatter and low explained variance in the relationship. This is because sediment delivery processes cannot be easily explained by a single (spatially and temporally lumped) parameter due to their complexity and their interactions with catchment characteristics (Walling, 1983; Worrall et al., 2014). Analysis of 877 rivers worldwide, for example, showed that the differences between SSY for basins of the same size may be up to four orders of magnitude indicating clear stratification of the data according to geographical region and maximum basin altitude (de Vente et al., 2007). Similarly, analysis of a large European SSY dataset also indicated a generally weak and very scattered relationship between SSY and A that showed clear differences for different climatic regions and topographic zones (Vanmaercke et al., 2011). Therefore, different region specific SSY-A relationships can yield stronger correlations than a single, global, relationship and can be generally more reliable (de Vente et al., 2007).

As relating SSY to catchment area alone can be troublesome, regression equations that include other explanatory variables are generally more robust (e.g. Ayadi et al., 2010; Verstraeten and Poesen, 2001). Apart from catchment size, topography and climate are generally considered to be significant factors controlling sediment yields at a global scale (Jansen and Painter, 1974; Milliman and Syvitski, 1992; Syvitski et al., 2003; Syvitski et al., 2005; Walling and Webb, 1996). Adding more factors to the equation, such as discharge, geological and human variables can improve sediment yield predictions (e.g. Syvitski and Milliman, 2007). As erosion and sediment transport processes are the product of many interacting hydroclimatic, geomorphological and lithological factors, a combination of those factors can be expected to yield the most significant regression models (Ludwig and Probst, 1998). However, the importance of each controlling variable may vary between different regions and at different scales and therefore a number of different factors may be explored and used in such predictions. These can be summarised as: scale factors (e.g. catchment size), climatic factors (e.g. mean annual precipitation, rainfall intensity, mean annual temperature), hydrological factors (e.g. mean annual runoff, maximum/mean water discharge), topographic settings (e.g. mean elevation, relief, slope), soil and lithology characteristics (e.g. soil erodibility, fraction of clay/marl area) land-use/land cover (e.g. percentage vegetation cover, arable cultivation practices, land-use composition and patterns (e.g. patchiness)), human impact factors (e.g. human footprint index, soil and water conservation practices, population density, livestock density, fractions of cultivated and forest land) and drainage network characteristics (e.g. total drainage length) (e.g. Ali and de Boer, 2008; Ayadi et al., 2010; Balthazar et al., 2013; Buendia et al., 2016; de Vente et al., 2011; Grauso et al., 2008; Restrepo et al., 2006; Shi et al., 2014; Xin et al., 2011). More recently, Vanmaercke et al. (2014a) and Vanmaercke et al. (2014b) highlighted the influence of seismic activities in explaining SSY in undisturbed European and African catchments which can account for more influences than topography alone, explaining factors such as increased erosion rates due to tectonic uplift, earthquake triggered mass movements and weakened surface lithology.

Typically, regression based sediment yield models focussed on estimating long-term average annual sediment yield. While this is particularly useful for explaining spatial factors influencing differences between average SSY for different catchments, it does not account for important inter-annual temporal variability in sediment yields within each catchment, which may be of particular interest to water resource managers. Moreover, lack of sufficiently long records in each catchment to adequately represent its average SSY introduces considerable uncertainty into such models, whereas the use of averaged climatic explanatory variables (that often may not even be derived for the same observation period as SSY) may mask the importance of climatic factors in SSY prediction.