Catena 165 (2018) 442–453

Contents lists available at ScienceDirect

Catena

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

Identifying a reliable method for estimating suspended sediment load in a temporary river system

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ARTICLE INFO

Keywords:
Temporary stream
Suspended sediment load
Load estimation techniques
Stratification of data
Uncertainty

ABSTRACT

Sampling strategies and methods used for estimating load can lead to large uncertainties in suspended sediment transport quantification, especially in rivers with a high variability in streamflow. The aim of this paper is to evaluate suspended sediment load, using a number of direct estimation techniques, in order to find a suitable method for temporary river systems, and to assess the uncertainty associated with load estimation, due to the specific method applied. One year of continuous measurement of flow, and discrete sampling (n = 216) of suspended sediment concentrations, taken from 2010 to 2011 in the Celone River (SE, Italy), were used to estimate annual load. Averaging, ratio, and regression estimator methods were applied to the entire dataset, and to subsets of data, to calculate load. The results show a wide range of values, from 220 to 1123 t km^{-2} yr^{-1}, with respect to the applied suspended sediment load estimation techniques. Averaging methods resulted biased. Sediment rating curves underestimated load, while, if the back-transformation bias correction was used, load was overestimated. The ratio methods generally overestimate load. Increased precision and accuracy was achieved through applying data stratification, based on flow regime and seasonality. After applying three different flow regime stratifications, the annual load ranged from 240 to 606 t km^{-2} yr^{-1} and, using seasonal stratification, from 258 to 974 t km^{-2} yr^{-1}. It seems that ratio estimator methods, and the regression equations applied to the stratification on a flow regime basis, are more suitable for estimating load in temporary, flashy streams.

1. Introduction

Most of the river basins influenced by the Mediterranean climate are affected by erosion and soil degradation. During the last few decades, there has been a significant increase in studies of erosion (de Vente et al., 2009), sediment transport dynamics (Gentile et al., 2010; Bisantino et al., 2010; Gallart et al., 2013; Regüés and Nadal-Romero, 2013; García-Rama et al., 2016; López-Tarazón and Estrany, 2017; Kheirfam et al., 2017), and load estimation methodologies (Letcher et al., 2002; Tabatabaei et al., 2014). Several models have been developed for quantifying soil erosion by water and wind, which have been applied on regional (Kirkby et al., 2008; Panagos et al., 2015; Vigiak et al., 2017) and basinal scales (Abouabdillah et al., 2014; Bagarello et al., 2017; Ricci et al., 2018).

Sediment load quantification is an important task in river basin management, as it provides the order of magnitude of soil loss. It is also fundamental in evaluating reservoir siltation, and the consequent loss of water reservoir capacity (Vericat and Batalla, 2006), and is necessary for calibrating models used to estimate erosion and sediment load. On the other hand, hydrological and sediment regimes are the basic drivers of water quality (Larned et al., 2010) and river ecosystems (Arthington, 2012; Wohl et al., 2015), and an accurate load estimation allows us to understand the impacts of anthropogenic activity on rivers.

Sediment load, transported in a certain time interval through a section of river, is quantified by integration of instantaneous flux, which is the product of suspended sediment concentration (SSC) and discharge (Q). This simple equation, in several cases cannot be applied, due to limited data availability. In a number of basins, at the most, measurements of streamflow are available on a daily time-scale, whereas SSC measurements are generally taken on a weekly or monthly basis (De Girolamo and Lo Porto, 2012). Hence, to calculate sediment load, it is necessary to estimate the concentrations for those days when no measurements are available. This is the so-called "load estimation problem" (Lee et al., 2016). Several direct techniques have been developed for estimating suspended sediment load by using infrequent samples of SSC and continuous measurements of Q (Asselman, 2000). The characteristics of the dataset (i.e. number of samples), the dimensions of the river basin, and the flow regime, play an important role in

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https://doi.org/10.1016/j.catena.2018.02.015
Received 5 December 2017; Received in revised form 8 February 2018; Accepted 12 February 2018

choosing a 'good' estimation technique, although every method has its limitations and bias rate. The most common methods are grouped into: *averaging estimation techniques* (Walling and Webb, 1988), *ratio estimation techniques* (Beale, 1962), and *regression estimation techniques* (Horowitz, 2003). Recently, new regression techniques have been developed that relate observed SSC to streamflow, or other variables (i.e. time, season) (Hirsch et al., 2010); the estimated daily concentration is then multiplied by daily streamflow to obtain load. Although a number of studies have analysed aspects concerning load estimation, few of them have focused on the 'load estimation problem' in temporary river systems. The extreme variability of the hydrological regime, which characterises temporary streams (Oueslati et al., 2015; De Girolamo et al., 2017a; De Girolamo et al., 2017b), involves objective difficulties in the continuous measurement of SSC (De Girolamo et al., 2015a; Wohl et al., 2015) and, at the same time, implies a high degree of uncertainty in the evaluation of suspended sediment load.

In this context, the first objective of the present paper was to estimate suspended sediment load in the Celone River (SE, Italy), a typical temporary river, by using methodologies commonly applied to perennial rivers. The second objective was to identify a technique able to improve the accuracy of load estimations, reducing the uncertainty interval that can be applied to a temporary river system. Finally, by means of uncertainty analysis, we aimed to quantify the degree of confidence that users can assign to a given load estimation method.

Our final aim was to provide a guideline for watershed managers for selecting methods of sediment load estimation, and to contribute to improving the understanding of the "load estimation problem" in watersheds influenced by Mediterranean climate.

2. Materials and methods

2.1. Study area

The study area is the Celone River basin, located in northern Apulia (SE, Italy). The area of 72 km^2 drains into the Capaccio Reservoir, characterised by a full capacity of 25.82 Mm^3 (in May 2016, the filled volume was 16.8 Mm^3).

In the mountainous area, characterised by steep slopes, and in a phase of accentuated erosion, the river channel is incised, and a large amount of suspended and bed load material is transported. Throughout the mountainous area, many check dams have been built to reduce bank erosion. The main channel assumes a shape of twisted channels in a flood plain, where most of the coarse material is deposited, and then continues with a meandering pattern. The drainage network of the basin assumes a dendritic pattern. The main river channel is about 24 km long, and the entire drainage network is about 80 km long.

The main lithological units are flyshoid formations (flysch della Daunia) and grey-blue clays in the upper part of the basin, and alluvial deposits in the valley. The main soil types are classified as typic-haploxerroll, vertic-haploxeroll, and typic-calcixeroll, according to the US Department of Agriculture classification. The soils in the basin have a composition related to the lithology, and show a variable texture (clay, clay-loam, and sandy-clay-loam). The depth and soil physical and hydrological characteristics are highly variable; in the flat part of the basin, soils are deep (1.5–2 m), while in the hills and mountains, they are moderately deep (< 1 m).

The area is an agricultural basin; the main cultivations are cereals (mostly winter and durum wheat; 45%), sunflower (9%), pasture (6%), and olive groves (8%). Minor land uses (2%) include vegetables and vineyard. Forests (29%), mostly oaks and conifers, are present in the upper part of the basin. Urban areas (1%) are limited to three small villages; therefore, the human pressures contributing to soil erosion in the area are agricultural practices, especially conventional tillage that involves multiple operations with chisel plow and disks. In autumn and winter, most of the agricultural areas are not protected from erosion (seeded and ploughed fields for spring crops). The erosion is favoured by up and down tillage, which is employed in the mountainous and hilly parts of the basin. The erosion processes in the area are both distributed (sheet erosion) and localised (rill erosion). Erosion of the banks is also an active process.

The climate in the Celone Basin is typically Mediterranean; rainfall events are mainly concentrated in winter and spring, and frequently occur for short durations and at high intensity. Precipitation also shows a high spatial variability, with events localised in small areas. The rainfall regime has a great influence on the flow regime of the Celone River, which is characterised by periods of intermittency of flow and flash floods and, consequently, on erosion and sediment transport. In the period 1960–1996, the average annual precipitation amount to 792 mm in the mountainous area (Faeto; 860 m a.s.l.), and 623 mm in the lowland area (Troia; 350 m a.s.l.). Mean temperature varies between 3.4 °C (January) and 20.3 °C (August) in the upper part, and between 7.2 °C (January) and 25.5 °C (August) in the valley (De Girolamo et al., 2015b; De Girolamo et al., 2017a).

2.2. Field data: Streamflow and suspended sediment concentration

From July 2010 to June 2011 (12 months), continuous measurements of streamflow, and infrequent measurements of SSC, were recorded at the Masseria Pirro gauging station, 8 km upstream of the Capaccio Reservoir (Fig. 1). An ISCO automatic sampler (model 6712FS; 24 bottles; pumped volume 1 L) was installed in the gauging station, which is connected to an ISCO 750 Area Velocity Flow Module, in order to have continuous measurements of the streamflow. Two sets of programming were used. The first one lets us set up time-spaced samplings. With this standard program, periodic samples were taken at fortnightly or monthly time intervals during summer and autumn periods, and once or twice a week from November to June. The second set lets us create complex programs for flood sampling applications. We adopted a sampling strategy triggered by water level changes during the rising limb of hydrograph and flow rates during the flood recession. During flood events, the time-interval was between 15 min and 2 h in the rising limb and between 2 h and 1 day in recession limb. With this sampling program, a large number of samples were collected over the study period (n = 216), covering all hydrological conditions (flood, normal, and low flow). The SSCs were analysed in a laboratory, using the APAT-IRSA analytical standard method (APAT-IRSA-CNR, 2003). Standard 0.45 μm pore-diameter cellulose filters were used to filter the samples, to quantify the total suspended concentration. For additional details concerning the gauging station and sampling, please refer to De Girolamo et al. (2015a).

The study period is representative of historical hydrological conditions in the basin (Table 1). We verified that rainfall recorded in two gauging stations was 43% and 2.4% higher than historical data (from 1960 to 1996). Whilst, the most relevant flood events are comparable to the major events recorded in the past at San Vincenzo gauge, an old station located 8 km downstream the new one (Masseria Pirro) (recurrence interval of 30 years).

2.3. Load estimates

The flux of sediment passing through a cross-section of a stream during a predetermined time-interval can be expressed mathematically by the relationship (Eq. 1):

$$L = \int_{t1}^{t2} Q_t SSC_t \, dt \qquad (1)$$

, where Q_t is the streamflow (L s^{-1}) at time t, SSC_t is the SSC (mg L^{-1}) at time t (s), and L is the load (mg).

To apply this relationship, it is necessary to know how discharge (Q) and SSC vary over time. When the measurements of SSC are discrete, as in this case, a relationship describing the variation of concentration over time, between two consecutive measurements, SSC(t), is needed.