Sediment yield from mountain slopes: a GIS based automation of the classic Gavrilovic method

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Abstract

Sediment yield and slope erosion represent nowadays an open problem for Alpine river basins management. In the last decades a variety of methods to estimate erosion rate and yield volumes have been studied and presented to the scientific community; however these methods are often empirical and only provide rough results. On the other hand the use of physical based methods demands an enormous quantity of data that are difficult and costly to collect. Moreover these data are affected by an intrinsic error due to the impossibility of taking accurate parameter measurements. This paper focuses on the Gavrilovic method that is considered a standard for erosion evaluation in Alpine regions; this theory has proved to be effective and quite simple to be applied, but has a major drawback in the subjectivity of parameter determination. Since 1973, when this method was initially published, many things have changed and computers have revolutionized the scientific world. The authors are convinced that the use of a GIS support can automate the Gavrilovic method. GIS uses advanced calculation methods based on high resolution geographic data; these datasets allow one to eliminate or at least reduce the role of the operator in the calculation processes. Moreover the whole basin can be automatically split into little sub basins with similar features. This operation leads to an application field more similar to the original testing site. The final objective is to present an automated process that can produce a reliable prediction of sediment yield from little and medium basins starting from DTM and use of soil maps, taking into account also the rainfall distribution on the studied area. The new method is then applied to a test site to demonstrate the improvements in time and efficiency this innovation can lead to.
Keywords: Gavrilovic, sediment yield, soil loss, Alpine basin, GIS.

1 Introduction

Slope erosion is nowadays a widely studied phenomenon when studying topics about water resources and basins management. A great amount of studies usually focus on the sediment yield in open plains, with gentle slopes, where agriculture is the main activity and loss of fertile thin soil the main problem. Instead few efforts are directed in understanding and simulating terrain erosion in mountain and Alpine regions: in this case the objective is slightly different and more concentrated to hydraulic structures dimensioning and silting volumes evaluation. Sediment yield at basin scale is the product of all sediment producing processes and sediment transport within a basin (De Vente and Poesen [1]). However simulating all the processes going on in a basin, both a plain or Alpine one, is not possible. Some methods focus on rill and inter-rill erosion, others on gully and bank erosion (De Vente and Poesen [1]). Since the topic is composite and complex also calculation models follow this trend and over the years have grown on complexity, until they become almost too complex to be correctly applied in real cases. As stated by Renscheler and Harbor [2] the use of commonly available data in place of expensive research data have a significant impact on models results; this point is basic and should be carefully considered. Is it useful to make efforts to develop extremely complex models if input data are, due to economical limitations, of low quality? Starting from this point of view some physical based models have been analysed and their input data discussed, in particular EUROSEM (Morgan et al. [3]) WEPP (Flanagan et al. [4]) SWAT (Arnold et al. [5]) and Bemporad et al. model ([6]). While the first two models are completely physics-based, the last two are conceptually based. EUROSEM was born in the nineties with the aim to build a model which should become the state of the art, referring to soil losses and sediment yield; due to this ambitious objective it encloses all the most advanced, and by the way complex, models for each single process involved in soil loss. When trying to apply EUROSEM, is necessary to build a huge database of data that includes all aspects of simulated basin, from easy to collect data, as DTM or soil use, to hardly estimable ones, like the percentage of soil covered by trees trunks or the amount of water flowing along the trunks. An estimation of the percentage of soil covered by rocks and boulders and so protected by erosion is request too. Such an approach is not suitable for a fast assessment of soil loss and moreover data collection is a crucial step of the work, since data uncertainty will invalidate the whole model reliability. A similar reasoning can be done about WEPP, although it implies the use of more common data, they are far from normally available data. Conceptual model like SWAT and Bemporad have to be fed with more easy to collect data, offering a good results to cost ratio. SWAT has been developed thinking to USA plains and has no specific development for Alpine regions needing some effort to adapt it. At last some information about Bemporad et al. model is supplied: this is a distributed model developed by ISMES (Istituto sperimentale modelli e strutture) to forecast silting in Alpine dams. The method couples a hydrological model with a sediment production model, which is borrowed straight from Gavrilovic [7], neglecting sediment routing. Although the required database is easy to be built the model takes a long computation time to get to its results and relying on Gavrilovic formula cannot be considered autonomous from this. In this work the well known USLE-RUSLE (Universal Soil Loss Equation-Revised USLE) models have been intentionally neglected because of their empirical approach, based on agricultural terrain database, will not adapt to Alpine regions, as tested by Longoni et al. [8] and Tazioli [9]. Finally Gavrilovic formula has been chosen due to its balance between easily collectable data request as input, fast execution and fairly good results: the objective is now to integrate it in an automatic GIS module, which will avoid operator to subjectively choose parameters values and can handle also wide basins always with the same detail scale of little experimental plots.

2 Gavrilovic method

Since 1963 S. Gavrilovic started an extensive study campaign to better understand soil loss phenomena and sediment yield from Alpine and semi Alpine region. All the work of S. Gavrilovic has been summed up after more than 20 years of experimental observation in a work by Gavrilovic [7]. The method, called Erosion Potential Method, is fully empirical and relies only on easy collectable data and simple mathematical formula; thus the formula will often give incorrect results or with a high level of uncertainty if not carefully used. Now the formula will be presented and discussed in order to underline each parameter source and influence. Z. Gavrilovic in his work suggests to collect data directly on field and draw them on an adequate scale map, or to rely on aerial photography. These guidelines leave the choice of values to operator personal discern. The formula starts mapping three different coefficients named: Φ, X_a and Y. The first is called Observed Erosion Coefficient and is graded into ten values ranging from 0.1 to 1.0 and express the level of present erosion, following a reference table supplied in original work (Gavrilovic [7]); the estimation is a matter of visual estimate and requires a certain experience (Gavrilovic [7]). Xa is land-use coefficient and should be estimated by aerial photos and deals with terrain coverage type: for instance woods, crops, hay meadows, bare soil and so on; values range from 0.05 to 1.0 and are indicated in a table included in the original paper (Z. Gavrilovic [7]). Last, Y is coefficient of soil resistance to erosion and depends by the pedological classes of soil, in his work Z. Gavrilovic gives a table of values also for this parameter. These values are combined together to obtain Z, the erosion coefficient.

$$Z = Y \cdot Xa \cdot \left(\Phi + I^{1/2}\right) \tag{1}$$

where: - I is average land slope.

The next step calculates the sediment production:

$$W_{sp} = T \cdot H \cdot \pi \cdot Z^{3/2} \tag{2}$$

where: - W_{sp} is average annual specific production of sediments
- T is a temperature factor calculated with the formula:

$$T = \left(\left(t/10\right) + 0.1\right)^{1/2} \tag{3}$$

where: - t is the mean annual temperature in Celsius degrees
- H is mean annual amount of rainfalls in millimetres/year
- Z is coefficient of erosion previously calculated.

So the average annual production is simply W_{sp} times the area F measured in square kilometres. This value represents the total amount of sediment produced in the basin, which, although there is a strong relationship is not the amount of sediment which arrives in the closing section of the basin. So a routing parameter R is introduced:

$$R = \frac{4 \cdot (O \cdot D)^{1/2}}{(L + 10)} \tag{4}$$

where: - O is the perimeter of basin
- L is length of the main water course
- D is mean level difference in basin, that is to say the difference between the mean altitude of basin and the level of closing section.

At the end the value of sediment routed to closing section is calculated as:

$$G = W_{sp} \cdot F \cdot R \tag{5}$$

where F is basin area. Speaking about parameters origin they can be divided into two classes: geometrical ones and qualitative ones. While geometrical data can be measured in a bunch of different ways, achieving the precision needed by the formula, qualitative parameters such as land cover or erosion resistance have to be estimated, by indirect means, observing aerial photos or making in situ classifications. Their precision will be low, with a high uncertainty level which will arise when applying the method to large basins. In order to improve this step of the work an innovative method, linking up to date GIS capabilities and classical Gavrilovic estimation table is presented.

Figure 1: Rossiga valley position on Italy map.

3 GIS application and automation

Since 1988, when Z. Gavrilovic presented the final version of his soil loss formula, computers have become a standard tool for any kind of work. The idea is to apply information technology to simple Gavrilovic formula in order to turn an empirical formula which needs extensive operator judgements to an automatic process with little, if not totally absent, operator influence and ideally applicable to basins of any dimension using little scale data. Applications like this have already been done with the more common USLE and RUSLE formulas, not suitable in Alpine regions as already seen, for instance by Baigorria and Romero [10], Jain and Debjyoti [11], Chou [12], Leombruni et al. [13] and Globevnik et al. [14]. The process has been tested on a little basin in Northern Italy called Rossiga valley. Rossiga valley has an area of 3.79 km^2 and is 100 km north of Milan, in 2002 the area was interested by major hydro-geological disasters, a big landslide detached just at north of Rossiga valley and the basin itself was interested by a noticeable debris flow which detached from three different areas in the lower part of Rossiga. This zone is well known by Politecnico di Milano which has studied extensively the phenomena in progress; moreover a good geographic database exists and contains all the useful information. In this paragraph the entire procedure will be presented step by step. First of all is necessary to collect all the needed maps, in the table 1 the used datasets are named and briefly explained. These data are available for all the Lombardy

Table 1: Datasets used.

Name	Description	Format	Resolution
DEM	Digital elevation model of terrain	Raster	1x1 m
DUSAF1	Use of soil and land coverage	Vectorial	/
Rainfalls	Mean annual rainfalls	Vectorial	/
Temperature	Mean annual temperature	Vectorial	/
Lithology	Main litho-types of terrain	Vectorial	/
Ortophoto	Aerial colour picture	Raster	0.5x0.5 m
CT10	Technical regional map, digitized by 1:10,000 military map	Vectorial	/

Region territory and are useful to determine all the parameters requested by the Gavrilovic model. Basically all geographic data are handled by EsriInc. ArcGis which can extract from these maps the numerical input for the Gavrilovic formula; these data exported as raster images are then processed with a simple Mathworks Inc. Mat Lab script that calculates the final results, both as a volume at closing section and as a map showing specific erosion values. Now for each parameter source data will be described and the sequences of operation that have been done to prepare it for final elaboration are depicted.

3.1 Coefficient of observed erosion

This one is the only parameter that needs to be assessed by hand, evaluating the situation by aerial photography. At the moment is not possible, or at least non convenient, to develop an algorithm which can handle this delicate task. The picture was zoned by trained expert and the result is a raster image whose value represents the Φ value for each square metre cell.

3.2 Land-use coefficient

This coefficient is calculated starting from the DUSAF1 map. The territory is divided into homogeneous zones; each area has a feature called Description where the land coverage is stated. The first step has been the a priori assignation to each description of a correspondent X_a value. In DUSAF1 are included a variety of different description, in this resume table 2 only relationships used in Rossiga valley are shown. At this point the map has been turned into raster format giving to each cell the correspondent X_a value. Resolution has been set to 1x1m.

Table 2: Land-use coefficient values.

DUSAF1 Description	X_a value
Broad leaved Wood	0.20
Rocky outcrops or bare soil	1.00
Human buildings	0.00
Hay meadow	0.40
Pastures	0.60
Farmed Fields	0.63

3.3 Coefficient of soil resistance to erosion

This coefficient is calculated starting from a geological pedological map giving to each terrain type a proper Y coefficient value. Since the map is a raster this operation was performed simply reclassifying the original raster converting each class to the Y value.

3.4 Slope coefficient

The I coefficient or slope coefficient is derived from the DEM (Digital Elevation Model). For this area, as a consequences of November 2002 events, is available a high resolution DEM obtained from aerial laser scanning with a resolution of 1x1m. Using a built-in function of ArcGis a raster representing the slope is obtained, where the value of each cell is equal to the degrees of the slope. The conversion from sexagesimal degrees to percentage is than applied directly in Mat Lab script.

3.5 Temperature coefficient

A temperature T is needed to calculate the specific sediment yield from basins.

$$T = \left(\frac{t}{10} + 0.1 \right)^{1/2} \tag{6}$$

where t is the mean annual temperature posed equal to 7°C. This data has been taken from a meteorological station near the basin and then diminished by an empirical factor to consider height variations. The output is a raster.

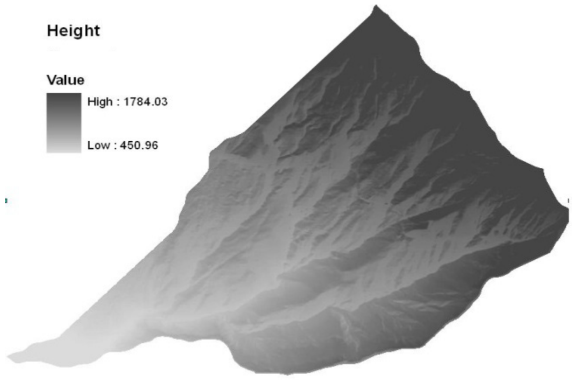

Figure 2: DEM of Rossiga valley.

3.6 Mean annual rainfalls

The parameter H is the mean rainfall value expressed in mm/year. For little basins, like the study case discussed in this paper, this value can be considered constant; in case of application on large basins, more than few square kilometres of area, a raster of mean rainfalls can be easily obtained by interpolating isohyet available.

In this study case mean rainfall is 1,575 mm/year.

3.7 Sediment retention coefficient

The sediment retention coefficient, that express the percentage of sediment produced that is routed to closing section, relies on absolute values that do not need to be produced as raster by ArcGis. Basin geometrical information such as area and perimeter or stream length in the basin are extracted from the CT10 map (Technical Map scale 1:10,000) as text and used directly as Mat Lab input.

3.8 Brief overview of calculation process

All the steps and operations, leading to final result, have been automated as far as possible; writing a code which will make all the operations from input files down to final results without human intervention, although possible, was beyond the scientific aim of this paper. The operations are divided into two main part: in ArcGis, after all the necessary layers have been loaded a Visual Basic Macro executes all the sequences of operations on databases and produces the output made of several 32-bit floating point raster, each one containing a parameter spatial distribution. Then Mat Lab is used, a little executable copied in the same directory of input files makes all the calculation requested by Gavrilovic formula. Geometrical fixed data, such as area and perimeter of basin are supplied via a formatted text file. The output is a TIFF file, were the value in each cell represents the Z value and a text file were basically the total volume in closing section is stated.

4 Results and discussion

The results coming from Mat Lab are of two kinds: a map representing the erosion coefficient Z for each cell and a total amount of sediment value, $W_{g,}$ at the closing section. The first one is in itself an advancement from classical Gavrilovic approach that is able to supply only a single value in m^3 representing all the material collected in the closing section, with no reference to its origin. So this is the first improvement granted by GIS technology application to classical empirical formulas; it should not be considered only a mere consequence of elaboration, since knowing where erosion is going to have place can lead to focus mitigation operas in certain areas neglecting others, or, in case of big basins, can underline most critical under-basins and stable ones. In figure 3 representing specific soil losses for Rossiga Valley two main features have to be noted: at a first glance Z shows his strong relation with slope and is obvious since the valley is most covered by forest; but the contribution of the three landslides detachment areas is clearly identified. This areas are catalogued as bare erodible soil with no or poor vegetation and actually are critical for soil loss. In other words mathematical implementation based on matrix gives to the Gavrilovic formula a space variability that cannot be achieved by standard application. Looking to automation advantages is quite obvious to underline how this script simply diminish the time needed near to zero; operator is only marginally involved in decisional process, removing subjective interpretation

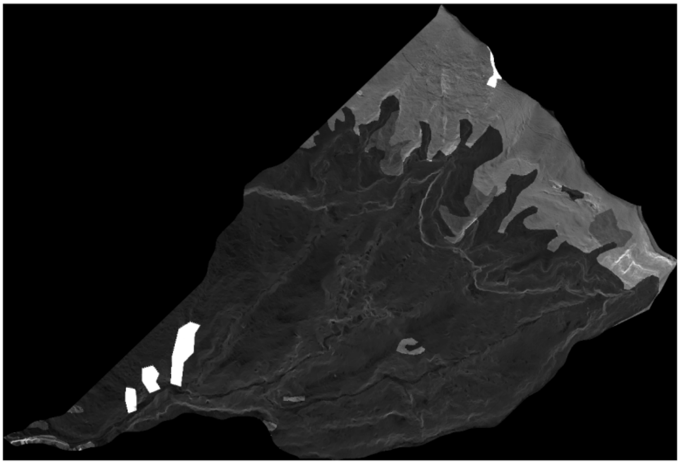

Figure 3: Z value for Rossiga valley, dark colours are for low values, bright ones for high values.

limits and, since operations to be performed on matrix are simple, CPU time usage is short allowing one to apply the method with high resolution also on large basins. Automation is not only a matter of avoiding man intervention in process, but permits to perfectly scale the method from very little basins to huge regional basins without introducing the needed approximation linked to limited human capabilities. When running Gavrilovic formula on extensive area operator have to make some approximations when choosing parameters values, since he cannot iterate thousands of times the same operations: computers have not this limit. It simply will take some more times but will continue to consider the best resolution data it has. Undoubtedly this is an important achievement. At last the total sediment yield calculated is 823 m^3, close to values calculated with others benchmark methods, like Bemporad et al [6], although requiring less time and interaction. Thus the GIS technology applied to Gavrilovic formula can be considered a full success, giving good results and diminishing execution time by several times.

5 Conclusions

This paper tries to make a step further in soil erosion prevision methods. Up to now methods to simulate these phenomena and their consequences have been divided into two big families: simple and not much effective empirical formulas and complex and very cost and time consuming physical based models. While scientific community seems to concentrate all its efforts in developing and testing new models this paper wants to renew a classical formula, concentrating on the possibility to improve its power using advanced technologies. The capability of Gavrilovic method, linked to good processing power of modern

CPUs and the availability of high resolution data for the whole Italian territory, proved to furnish reliable results. Authors do not want to neglect the need to upgrade knowledge of soil erosion phenomena and believe in the possibility to improve physical models up to a reasonable precision, but wanted to fill a gap. While international literature reports some example of USLE connected to Gis capabilities, such as Pandey et al. [15] and Jain and Debjyoti [11], little or no example of similar operations for Gavrilovic models have been done and since this formula appears to be the best for Alpine regions it seems a noticeable void that have to be filled. Final result of this work is an agile and light script that exploiting already existing databases and maps is able to return some indications about soil loss in a very quick and easy way. These data can constitute a valid, despite of its simplicity, result for preliminary assessment of erosion issues in Alpine region. Nevertheless it is important to point out how the semi automatic operation and the need of common data make it usable also by not highly specialized operators with limited budget. To summarize this paper is important to remember that the quest for new models and new technologies should not overcome the needs for flexible tools to be simply applied when looking for good results, enough for many applications, offering good quality effort ratio.

Acknowledgement

The authors want to gratefully acknowledge Regione Lombardia which allowed the use of geographic datasets for research purposes.

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