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A GIS BASED TOOL FOR THE SEDIMENT DELIVERY RATIO COMPARISON

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EXTENDED ABSTRACT

La nota descrive il funzionamento e i vantaggi dell'utilizzo di uno strumento informativo a base GIS, finalizzato alla determinazione del Sediment Delivery Ratio (SDR) per un bacino idrografico. Il Sediment Delivery Ratio è un indicatore utilizzato per determinare la capacità di un sedimento che è stato eroso dall'azione dell'acqua di raggiungere l'outlet del bacino.

I problemi causati dall'erosione del suolo sappiamo possono causare problemi quali la perdita di suolo e di produttività agricola nonché l'aumento della fornitura di sedimenti per i corsi d'acqua che hanno come conseguenza la degradazione della qualità dell'acqua. Nell'area mediterranea il principale motore di erosione e trasporto è l'intensità di pioggia oltre ad altri aspetti quali proprietà del suolo, vegetazione, morfologia. Proprio in questo ambito si inserisce quindi il SDR.

Tipicamente il valore di SDR viene determinato attraverso equazioni che contemplano parametri generali del bacino idrografico come ad esempio area, quota media, pendenza, drop in elevazione ecc. Queste equazioni hanno una funzione di black box dove in output è dato un generico valore medio di tutto il bacino. Questa informazione per quanto utile risulta comunque carente quando si deve programmare una corretta gestione e sistemazione dei versanti per capire quali sono le zone maggiormente contribuenti per quello specifico outlet individuato.

Il valore spazialmente distribuito del SDR fornisce informazioni molto importanti relativamente al processo di routing dei sedimenti dalla loro zona di origine fino alla sezione di chiusura del bacino. Attraverso la sua valutazione e la sua rappresentazione cartografica è possibile infatti dedurre l'effettiva perdita di produttività del suolo, il comportamento del trasporto solido dei sedimenti negli impluvi e nei corsi d'acqua, ottenendo anche informazioni sul degrado della qualità dell'acqua. Per tale motivo, la valutazione del SDR, abbinata all'approccio GIS, è stata già ampiamente utilizzata nella letteratura scientifica. Il tool è stato sviluppato nell'ambito del software geografico gratuito e open-source GRASS GIS.

I GIS forniscono un supporto fondamentale per una migliore previsione del SDR, poiché possono considerare la variabilità spaziale dei fattori che influenzano i processi di routing dei sedimenti. Attualmente non esiste uno specifico modulo GIS per stimare la variabilità spaziale di questo parametro.

È stato pertanto implementato un modulo GRASS GIS (in linguaggio python) denominato r.sdr, dove il valore del SRD viene valutato mediante procedura GIS, utilizzando diverse equazioni della sua stima disponibili in letteratura. Il tool è stato applicato ad un bacino idrografico campione, quello del T. Feo, situato nell'area appenninica dell'Umbria nord-orientale (Italia).

ABSTRACT

The note deals with a new tool implementation for evaluating Sediment Delivery Ratio (SDR) in a river basin, through GRASS GIS software. The definition of a spatially distributed value of SDR is a very important task as the sediment routing can affects losses of soil productivity, increase of solid transport in stream channels, and water quality degradation. For such reason the SDR evaluation, coupled with GIS approach, has been extensively used in scientific literature. Geographic information systems provide a fundamental support for a better prediction of SDR, since it can consider the space variability of factors influencing the sediment routing processes. Actually a specific GIS module to estimate the spatial variability of SDR does not exist. We implemented a GRASS GIS module (in python language) called *r.sdr* where the sediment delivery ratio is evaluated by GIS procedure using several equations available in literature. We applied the tool to the Feo Creek watershed, located in the Apennines area of northeastern Umbria (Italy).

***Keywords**: Sediment Delivery Ratio, GIS, soil erosion, DEM*

INTRODUCTION

Problems caused by soil erosion can include losses of soil productivity, increasing in sediment supply for streams, and water quality degradation. In Mediterranean area the sediment routing is mainly controlled by climate (in particular by the rain intensity), soil properties, vegetation, morphology. Model the sedimentary process of erosion – transportation – deposition is a really complex task due specially when it is required to evaluate the sediment yield for large areas. Normally in these case the most common approach is to estimate the gross erosion using RUSLE (Renard *et alii*, 1991), a simplified soil erosion model, and derive the sediment yield by using a sediment delivery ratio (SDR). The SDR is defined as the ratio of sediment yield to total surface erosion. The use of SDR owes its origin to the observation that using erosion predicted by the RUSLE overestimates the amount of sediment delivered from hillslopes. RUSLE, in fact, does not account the deposition of sediment occurring on hillslopes. Therefore, an accurate prediction of SDR is an important challenge for a sustainable natural resources development and, in general, for environmental protection. There is no precise procedure to estimate SDR, although the USDA (1972) has published a handbook in which the SDR is related to drainage area; nevertheless, SDR can be affected by several other factors including soil texture, slope/lenght, land use, sediment source, nearness to the main stream.

Geographic Information Systems provide a fundamental support for a better prediction of the SDR. The GIS can consider the variability of factors influencing the sediment routing processes and they have been used extensively to model the SDR in several basins around the world (Weifengand Bingfang, 2008; Lu *et alii*, 2006; Kothyari & Jain, 1997; Jain & Kothyari, 2000; Lim *et alii*, 2005). De Rosa *et alii*. (2016) used a GIS procedure for sediment yield estimation for a large portion of Tiber River Basin in order to evaluate the ”pitfall effect” of numerous small agricultural reservoirs present in this area. Any small agricultural reservoir perform a function of small dam in rivers intercepting the natural sediment routing; this “trap effect” is here defined ”pitfall effect”.

This study starts from the GIS procedure used and implement a GRASS GIS (GRASS Development Team, 2016) module, in python language, called *r.sdr* where the Sediment Delivery Ratio is evaluated by GIS procedure by using several SDR equations available in literature. The new version of the code is now available even released on the github pages: https://github.com/pierluigiderosa/r.sdr/blob/master/r.sdr2.py. Such new version implements other new tools for the SRD estimation and run much faster in large basin and in high resolution DEM rasters.

METHOD

Significant research has been performed to estimate the SDR, finding that SDR is mainly related to watershed size. Normally Authors propose a correlation between SDR and watershed as the SDR curve (USDA, 1972). The *r.sdr* module uses several SDR curve based on watershed size because of its simplicity. Vanoni (2006) proposed a power function (Eq. 1) derived from the data for 300 watersheds, to develop a generalized SDR curve. Boyce (1975) and USDA (1972) also developed SDR curves (Eqs. 2 and 3, respectively). The last equation inserted (4), proposed by William & Berndt (1972), complains the average slope along the stream.

Vanoni 2006

$$SDR=0.4724A^{-0.125} \quad (1)$$

where, A=watershed area (km^2)

Boyce 1975

$$SDR=0.3750A^{-0.2383} \quad (2)$$

where, A=watershed area (km^2)

SRD USDA 1972

$$SDR=0.5356A^{-0.11} \quad (3)$$

where, A=watershed area (km^2)

William & Berndt

$$SRD=0.627S^{0.403} \quad (4)$$

where, S is the average gradient along river

A newer approach calculates the SDR ratio for a cell from the Conductivity Index (IC) following VIGIAK *et alii* (2012). The IC index takes the assumption that the SDR depends on two different approaches dominated by the geometrical topographical properties of watershed and drainage path:

- the upslope approach uses the characteristics of the drainage area where the SDR decreases with respect to increasing basin size: large basins have a lower average slope with more sediment storage sites located between the sediment source areas and the outlet;
- the downslope approach takes into account the flow path length that a particle needs to travel to arrive at the nearest sink. Larger is the path length, greater is the chance that sediments do not reach the basin outlet.

The IC uses both approach listed above, as showed in Fig. 1, and it is defined as:

$$IC = \log_{10}\frac{D_{up}}{D_{dn}} = \log_{10}\frac{CS\sqrt{A}}{\sum\frac{d_i}{C_iS_i}}$$

where:
- C is the average C factor; C factor is the crop/vegetation and management factor provided by USLE/RUSLE equation (RENARD *et alii*, 1991) of the upslope contributing area;
- S is the average slope gradient of the upslope contributing area (m/m);
- A is the upslope contributing area (m^2);
- d_i is the length of the flow path along the ith cell according to the steepest downslope direction;
- C_i and S_i are the C factor and the slope gradient of the i_{th} cell, respectively.

The SDR is calculated, for the i_{th} cell with the following equation.

$$SRD_i = \frac{SRD_{max}}{1 + e^{\frac{IC_o - IC_i}{k}}}$$

where SDR_{max} is the maximum theoretical SDR, set to an average value of 0.8 (VIGIAK *et alii*, 2012), and IC_0 and k are calibration parameters. In our model IC_0 have been set to 0.5 and k equal to 2. The values of the calibration parameters were derived following the indications proposed by CAVALLI *et alii* (2013).

The *r.sdr* module uses the above equations to define a spatially distributed SRD. The *r.sdr* produces a raster output where the SDR is estimated point by point. Area based methods calculate for each cell the upstream drainage area, from DEM preprocessing, by the GRASS GIS modules *r.watershead* and *r.water.outlet*, and deriving the SDR using the above equations. The figure 1 shows the workflow used in the *r.sdr* module.

In particular some preliminary operations are necessary, as fill sinks or smoothing DEM, for the further operations. In order to calculate the drainage direction, the Multiple Flow Direction

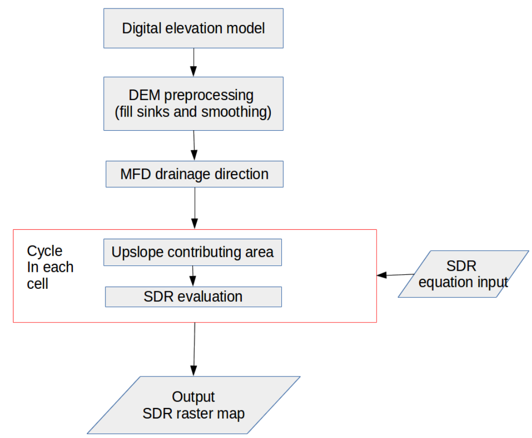

Fig. 1 - Workflow diagram for the r.sdr GRASS GIS module implemented city ruins and fires (Open source image)

MDF method, as proposed by HOLMGREN (1994) is applied.

The developed module is able to calculate the Sediment Delivery Ratio using a total of 5 methods: the general ones of VANONI, BOYCE, USDA and WILLIAM and the more sophisticated one of VIGIAK. The code in fact, during its run, writes on the screen the SDR values for the 4 methods indicated above, as well as providing the detailed mapping of the SDR with the VIGIAK method.

STUDY AREA

The study area covers the basin of the Feo Creek, which is located in the Apennine area of northeastern Umbria (Italy) and flows in the Gualdo Tadino Plain (Fig. 2). The catchment area is 9 km^2 and the average elevation is 1157 m a.s.l. The main stream, Feo Creek, is 6.4 km in length and has a very high average gradient (14.2%). The digital elevation model used in this study area is the TINITALY/01, presented in 2007 (TARQUINI *et alii*, 2007).

In the whole watershed of the Feo Creek carbonate rocks outcrop, members of the sedimentary "Umbrian-Marchean Series", from "Calcare massiccio" formation (Lower Lias, consisting in limestones in shelf facies), up to calcareous formations of pelagic environment ("Corniola", "Calcari diasprini", "Maiolica", "Marne a Fucoidi" and "Scaglia Group") of Jurassic-Eocene. All formations are intensely fractured and affected by tectonic contacts (above all normal faults), broadly distributed in the watershed.

These lithological and geological-structural characteristics favor an abundant production of debris that often invade the narrow valleys of the Feo Creek watershed and can be mobilized when particularly intense meteoric events occur.

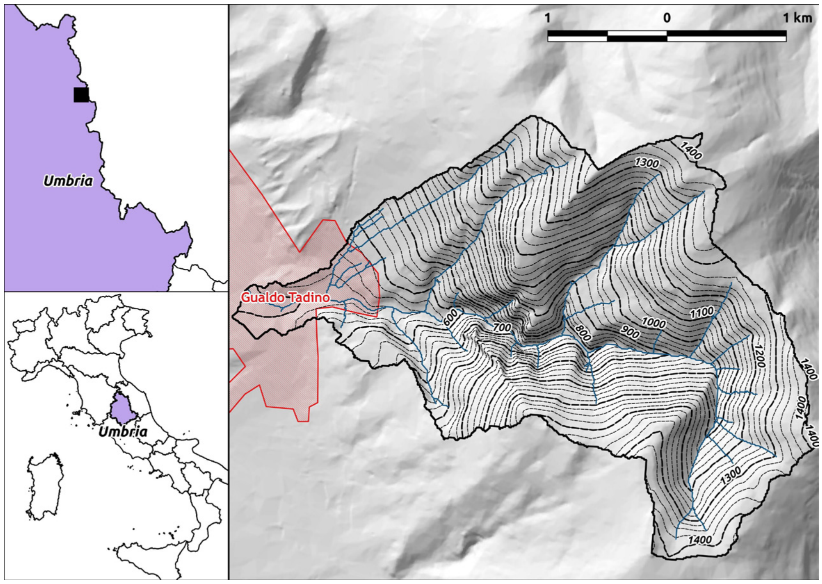

Fig. 2 - Study area boundary (watershed of the Feo Creek), located in the Apennine area of northeastern Umbria (Umbria-Marche internal ridge)

RESULTS AND DISCUSSIONS

The *r.sdr* have been applied using a DEM from Feo Creek in order to derive several SDR maps by using the different approaches here proposed.

The code also calculates some morphometric parameters necessary for the determination of the SDR as indicated by the general methods indicated above. The following table shows some of the outputs provided by the calculation code.

Table 1 shows in particular the values of the basin area, the mean slope and the mean gradient. The difference between

Mean slope	0.165231
Mean gradient	0.158942
Basin area	7.807333
SDR Vanoni (2006):	0.3654
SDR Boyce (1975)	0.229846091897
SDR USDA (1972)	0.451163651967
SDR Williams and Berndt (1972)	0.298790459567

Tab. 1 - Detail of the calculations carried out by the r.sdr module for the study basin

slope and gradient is the following: the gradient is calculated as the ratio of the difference in altitude between the furthest point of the basin and the outlet, and the length of the main stream; the slope is given by the average of the local slope along all the cells representing the main stream. Once these parameters have been determined, the code provides the SDR value according to the 4 methods: it can be noted that the values obtained are extremely variable, from a minimum of 22% (Boyce) to a maximum of 45% (USDA).

In addition to this table, the code produces in output, as already mentioned, a raster cartography which represents the distribution of the SDR value. For each cell, the value contained in it shows the percentage of sediments which, starting from that cell, are able to reach the outlet of the basin itself.

The figure 3 shows the SDR raster map, output of the *r.sdr* module, derived from the most complex equation (Vigiak *et alii*, 2012). Furthermore, in the same Fig. 3 it is clearly evident that the cells of the streams are characterized by higher SDR values than those of the slopes, since the sediments present in the streams are more likely to reach the exit of the basin compared to those present on the slopes. This information is obviously much more complete and exhaustive than the results of the other proposed methods, which refer to the basin as a whole and which fail to give a more accurate and distributed reading of the information. In order to complete the information deducible from the map of figure 3, a histogram was also created which represents the distribution of the SDR values in the whole basin. The histogram shows that the SDR ranges from about zero to 0.5 with a median of 0.05 and a mean of 0.011. This means that for the study basin the global SDR obtained with the Vigiak method is equal to 11%. This value is much lower than the values of the other methods but it is able to take into account the characteristic of the basin which in its central part has a morphological depression that acts as a trap effect for sediments. The abrupt change of SDR values showed in figure 3 in the left part of the basin is related to the particular morphological characteristics of the watershed: the graphical representation highlights the ”threshold effect” produced in the middle part of the basin where two thin ridges converge to the main stream. In fact, downstream the point where the SDR reaches highest values (in red in Fig. 3) sharply its value decreases due to the increase of upslope contributing area.

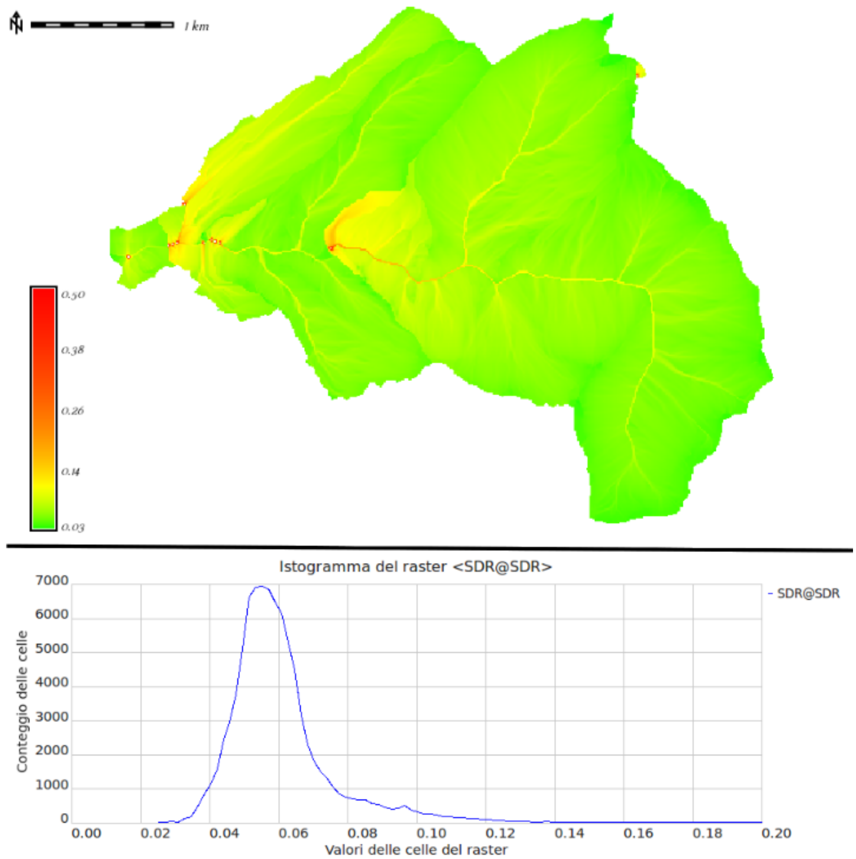

Fig. 3 - Sediment delivery ratio raster map calculated using the Vigiak *et al. (2012) formula, by means of the Connectivity Index. The figure at bottom shows the histogram distribution for the SDR values over the studied basin*

CONCLUSIONS

This work is the first implementation of a GRASS GIS module for a spatially distributed Sediment Delivery Ratio estimation. The module, called *r.sdr*, takes as input a digital elevation model and the user have to select the SDR equation. The definition of a spatially distributed value of SDR can provide useful information regarding the sediment routing processes, solid transport in streams, water quality degradation, and frequency increase of natural disasters such as mudflows. For such reason the SDR evaluation, coupled with GIS approach have been extensively used in scientific literature. Moreover, it does not exist a specific GIS module implemented to estimate the spatial variability of SDR. The *r.sdr* uses GRASS GIS since that software already provides some powerful module to pre-process the digital elevation model. *r.sdr* is able to drives the user, in a smooth way, to evaluate the SDR using as input only a DEM; all intermediate raster map (as smoothed and sink filled DEM) required to calculate the upstream component and the downstream component of IC and, afterwards, the SDR map are computed internally through internal module of GRASS GIS, or by the means of internal routines. The *r.sdr* module is freely downloadable and accessible from the internet at the site: https://github.com/pierluigiderosa/r.sdr/blob/master/r.sdr2.py, with an open source license and can be modified for your own need for research. The code currently calculates the sediment delivery ratio according to 5 methods: 4 are global methods that work as a black box, considering some global parameters that provide the SDR value for the entire basin. Such methods are the method of Vanoni 2006, Boyce (1975), USDA 1972, Williams & Berndt. In addition to these methods, however, the module *r.sdr* also implements the Vigiak method which, starting from the basin Connectivity Index, provides the SDR value for each cell of the study basin. This reading of the SDR is obviously much more detailed and guarantees a much clearer reading of the territory. For example, in the case study, the trap effect produced by the morphological depression present in the central part of the basin is highlighted.

Future software developments will be pointed in the implementation of further method for a spatially distributed SDR and in the implementation of an internal method for the weight map.

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