A GRASS tool for the Sediment Delivery Ratio mapping

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ABSTRACT

This work involves a tool implementation for evaluating Sediment Delivery Ratio (SDR) in a river basin, through GRASS GIS software (GRASS Development Team, 2016). The definition of a spatially distributed value of SDR is a very important task as the sediment routing can affects solid transport in stream channels, water quality degradation, and frequency increase of natural disasters such as debris flows and mudflows. 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 SDR 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, water quality degradation, and frequency increase of natural disasters such as debris and mudflow. In Mediterranean area the sediment routing is mainly controlled by climate (in particular by the rain intensity), soil proprieties, 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 al., 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, but SDR can be affected by several other factors including soil texture, slope/lenght, landuse, sediment source, nearness to the main stream.

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SDR. The GIS can consider the space variability of factors influencing the sediment routing processes and they have been used extensively to model the SDR in several basins around the world (Weifeng and Bingfang, 2008; Lu et al., 2006; Kothyari and Jain, 1997; Jain and Kothyari, 2000; Lim et al., 2005).

De Rosa et al. (2016, in press) 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.

METHOD

Significant research has been performed to estimate the SDR, finding that SDR is mainly related to watershed size. The correlation between SDR and watershed size is known 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).

$$SDR = 0.4724A^{-0.125} \tag{1}$$

where, A = watershed area (km^2)

$$SDR = 0.3750A^{-0.2382} \tag{2}$$

where, A = watershed area (km^2)

$$SDR = 0.5656A^{-0.11} \tag{3}$$

where, A = watershed area (km^2).

A newer approach calculates the SDR ratio for a cell *i* from the *conductivity index* (IC) following Vigiak et al. (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.

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

$$IC = \log 10 \left(\frac{D_{up}}{D_{dn}} \right) = \log 10 \left(\frac{\bar{C}\,\bar{S}\,\sqrt{A}}{\sum_i \frac{d_i}{C_i S_i}} \right) \tag{4}$$

where $\bar{C}$ is the average C factor (C factor is the crop/vegetation and management factor provided by USLE/RUSLE equation provided by Renard et al. (1991)) of the upslope contributing area; $\bar{S}$ 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 i_{th} 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 equation 5

$$SRD_i = \frac{SDR_{max}}{1 + e^{\left(\frac{IC_0 - IC_i}{k} \right)}} \tag{5}$$

where SDRmax is the maximum theoretical SDR, set to an average value of 0.8 (Vigiak et al., 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 `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 MDF method, as proposed by Holmgren (1994) is applied.

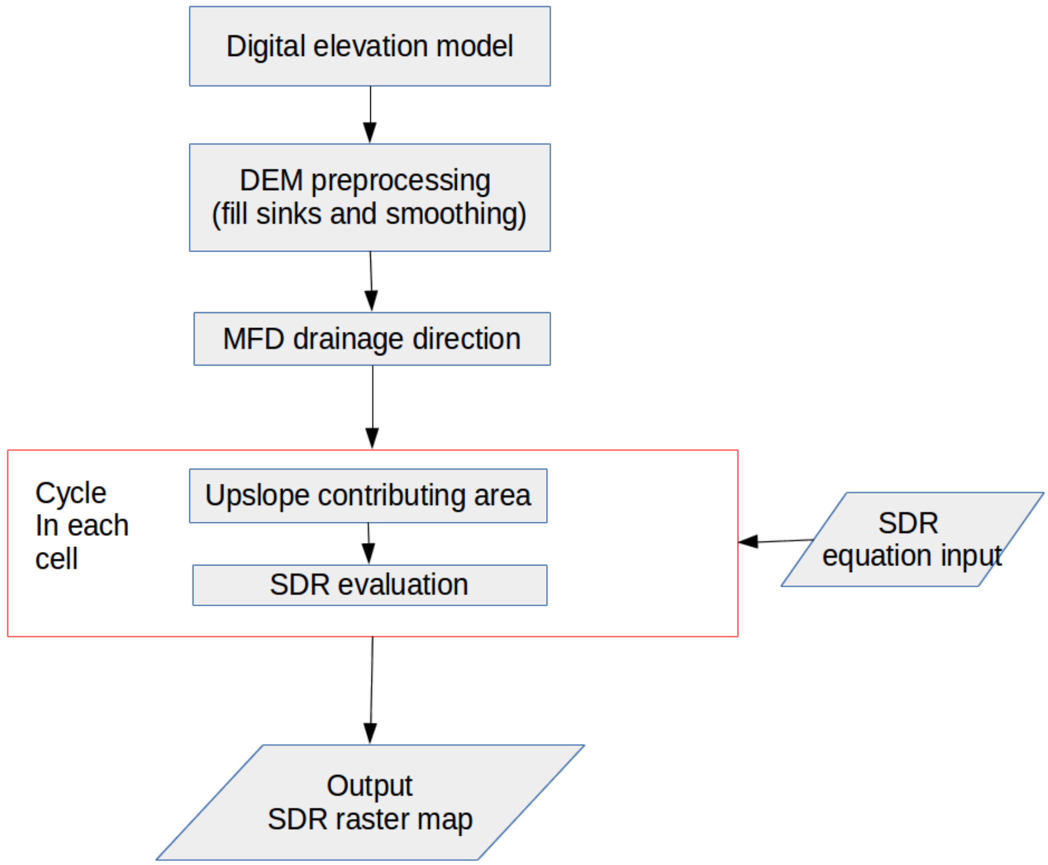

Figure 1. Workflow diagram for the `r.sdr` GRASS GIS module implemented

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 al., 2007).

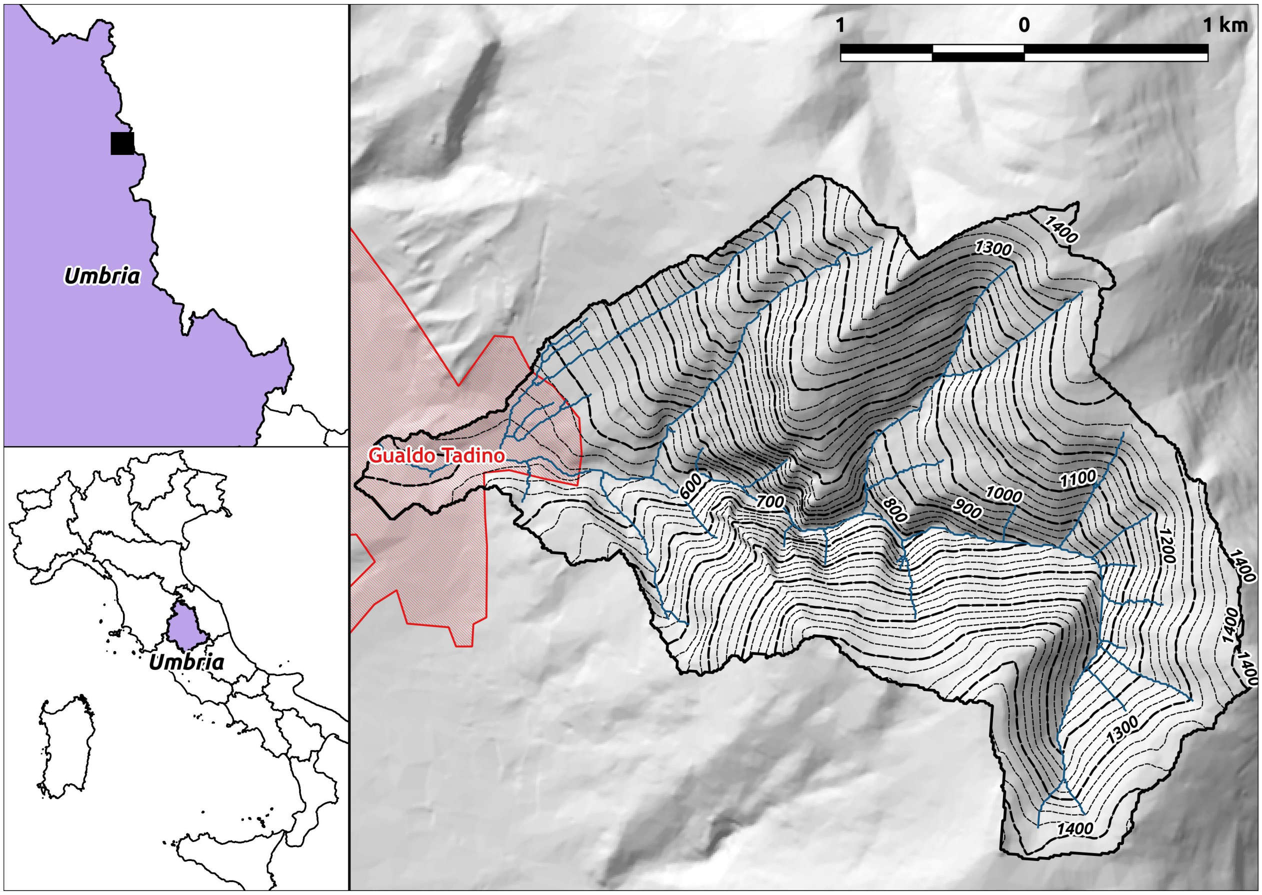

Figure 2. Study area boundary (watershed of the Feo Creek), located in the Apennine area of northeastern Umbria (Umbria-Marche internal ridge).

RESULTS AND DISCUSSION

The `r.sdr` have been applied using a DEM from Feo Creek (see section ”study area”) in order to derive several SDR maps by using the different approaches here proposed. The figure 3 shows the SDR raster map, output of the `r.sdr` module, derived from the most complex equation (Vigiak et al., 2012) . The represented histogram shows the SDR distribution over the whole basin that ranges from about zero to 0.5 with a median of 0.05.

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 figure 3) sharply its value decreases due to the increase of upslope contributing area.

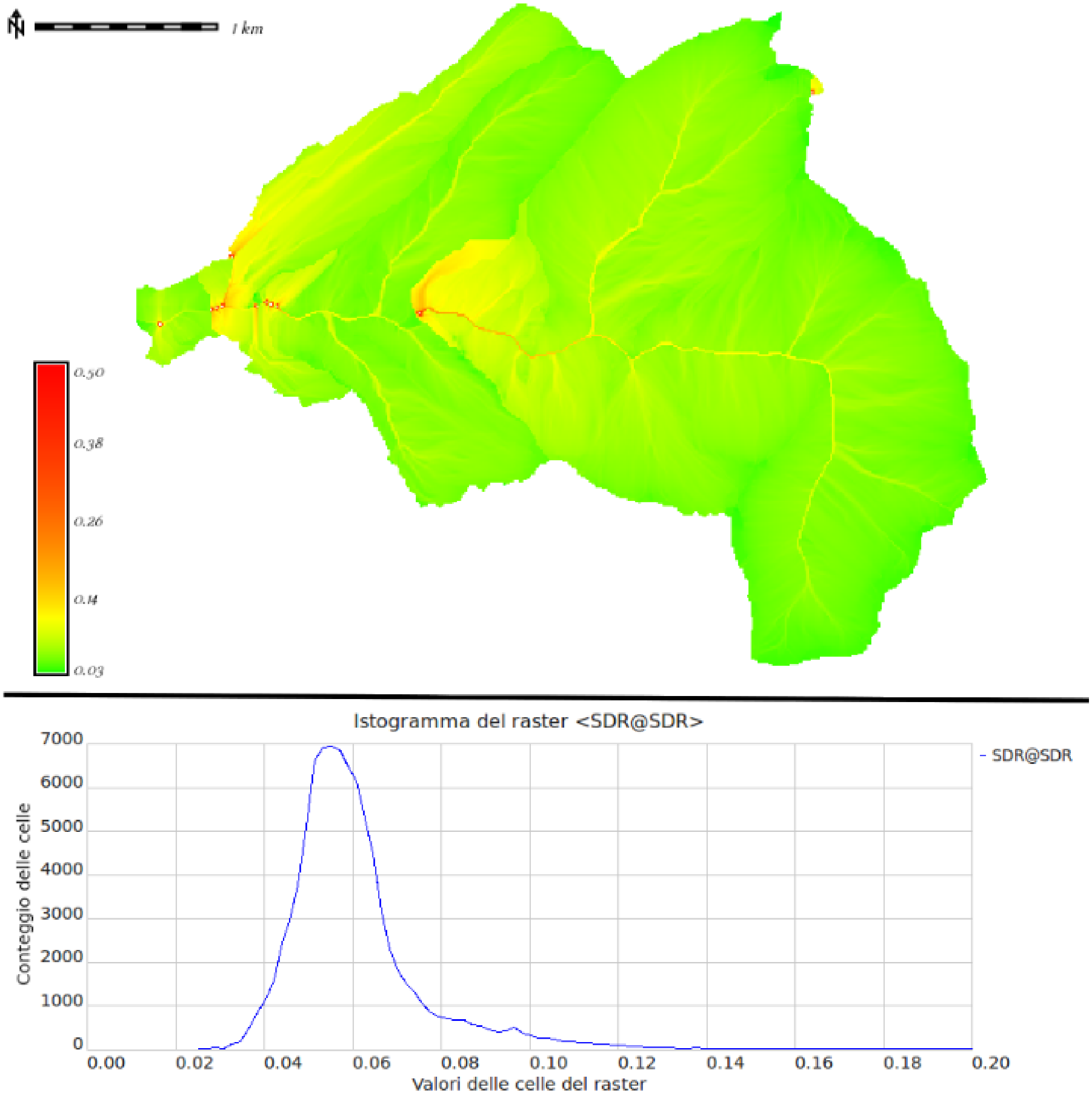

Figure 3. Sediment delivery ratio raster map calculated using the Vigiak et al. (2012) formula, from the *connectivity index*. The figure bottom shows the histogram distribution for the SDR values over the studied basin.

CONCLUSION

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

Univariate statistics	value ($0 \div 1$)
minimum	0.025163
maximum	0.503292
range	0.478129
mean	0.0616717
median	0.0585219

Table 1. Univariate statistics for the SDR raster map showed in figure 3. SDR is expressed as percentage between 0 and 1

provide useful information regarding the sediment routing processes, solid transport in streams, water quality degradation, and frequency increase of natural disasters such as debris flow and mudflow. 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.

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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