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Use of the USPED model for mapping soil erosion and managing best land conservation practices

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Abstract: The paper describes the implementation of the USPED model proposed by Mitasova et al. [1996] by the Romagna River Basin authority. The method is based on a detailed terrain analysis performed on a 10 m grid DEM, and includes an evaluation of the USLE K and C factors to predict soil erosion and deposition patterns at the landscape scale. The method is implemented within a GIS environment and used to map soil erosion hazard and to decide about land use constraints towards soil conservation. The predicted patterns are compared with those detectable in the field and with the prediction of the shallow landslide hazard predictor SHALSTAB (Dietrich and Montgomery, 1998). As a result, a guideline map for soil conservation is issued for use in practical land management. The paper describes the theoretical assumptions and limitations of the models used in the analysis, and delineates the potential benefits from such parameter-free and phenomenologic models in landscape pattern recognition and conservation.

Keywords: Erosion, river basin planning, soil conservation

1. INTRODUCTION

This paper describes the modeling strategy adopted by the Romagna River Basin Authority (RRBA) in the development of guidelines for soil conservation. This is a primary issue to be faced when planning the use of land subject to mass movements and soil erosion, and where agriculture has significant impact on overall river basin dynamics.

In the area of the Romagna river basins (Figure 1), soil erosion and conservation problems have been faced for almost twenty years, as appears from a number of publications [e.g. Chisci and Morgan, 1986], but the increased agricultural mechanization of the last decades has produced consequences which are still hard to recover and which delineate a landscape at risk of soil degradation. RRBA, which is the office charged with river basin planning in the region, considers the hilly agricultural areas prone to accelerated erosion due to lack of soil organic matter and proposed their admission in the national programme against soil degradation promoted by the Italian Ministry of Environment [Ministero dell’Ambiente, 1999].

As soon as geology is concerned, the region is structured as a typical sedimentary basin with low energy reliefs and extensive presence of badlands. Soil types include a variety of textural classes and are described at a relatively coarse scale by the Emilia Romagna Soil Map in scale 1:250.000 [Regione Emilia-Romagna, 1994].

Figure 1. Location of the area of the Romagna river basins

Because of the importance of soil erosion risk, many attempts have been made in the past in order to regulate agricultural practices and to address funding and other incentives deriving from the European Union (EU) agricultural and rural development policy to facilitate sustainable soil exploitation. However, a comprehensive approach to soil management with funding of sustainable practices is still waiting to be fully developed. The institution of the River Basin Authority at the end of the 90’s has created the opportunity to include soil conservation regulations in the wider
framework of the Basin masterplan, which is generally intended to give the rules for the implementation of good land use practices. The development of a consistent and comprehensive strategy at the landscape level means that the RRBA needs to develop a decision support system (DSS) suited to formulate appropriate rules which addresses the complexity of the phenomena involved.

2. MODELING LANDSCAPE SCALE EROSION PROCESSES

2.1 Model availability

In the past years, many models of soil erosion have been proposed. When detailed local evaluations are required, e.g. for engineering calculations relative to soil protection design [Pistocchi and Mazzoli, 2002], it is advisable to model the full process of soil erosion and deposition both in time and space. However, the development of either detailed, time-varying field scale models having strong physical bases (e.g. the EUROSEM [Morgan et al., 1998] or WEPP [USDA-ARS, 1997] models), or empirical models based on the account for many physical processes and variables and exploiting relevant experimental data (e.g. the RUSLE model [Foster et al., 1997]) is not applicable for landscape-scale predictions such as the ones required for river basin planning.

A different approach which has been increasingly pursued involves the modeling of patterns of soil erosion and deposition instead of the computation of absolute values of mass fluxes concerning sediment loss. This modeling strategy is suggested to be effective when facing planning issues for which a detailed engineering computation is not required [Morgan, 1995]. Obviously, modeling erosion/deposition patterns does not allow the evaluation of actual sediment dynamics and time variations of these patterns, but just the relative strength or intensity of the phenomena. However, it makes available a rationnel for the ranking of intervention priorities and maintains the possibility of comparing different management scenarios.

2.2 Model development at the RRBA

In this spirit, the RRBA has turned to consider landscape scale models as opposed to field scale ones. According to the popular RUSLE model, the “annual soil loss”, ASL, is given by:

\[ ASL = R K C P LS \]  

(1)

where R is the rainfall erosivity index, K is the soil erodibility index, C and P are the soil cover and management factors respectively, and LS is the slope and slope length factor. Many corrections have been suggested to account for landscape-scale effects. The basic idea in doing this has been to take the flow accumulation (drainage area) instead of the slope length to compute the topographic factor LS [Mitasova et al., 1996]. In this way, the index ASL of equation (1) is re-interpreted as a “transport capacity function” T:

\[ T = R K C P A^m (sin b)^n \]  

(2)

where the LS factor is replaced by the drained area A and the slope angle b, m and n being empirical coefficients whose value depends on the kind of erosion considered (either sheet or rill erosion). Note that the measure units of the above mentioned factors are not detailed here, because of their lack of meaning when pattern modeling is performed. Details can be found in Wischmeier and Smith [1978]. Equation (2) is a general formulation of transport models in terms of the hydraulic stream power made available for sediment transport [Mitasova et al., 1996]. The model hereby proposed for application simplifies equation (2) further by assuming that erosion-deposition patterns are not determined by the rainfall erosivity factor R, which is assumed uniform all over the region. In addition, no conservation practice is considered, so that P=1 according to its definition [Wischmeier and Smith, 1978]. Finally, factors K and C are to be dealt with as a combination of factors for both soil erodibility and soil cover due to vegetation, representing an ordinal scale of erosion susceptibility of the land while disregarding the effects of topography. Equation (2) becomes then:

\[ TP = Kc A^m (sin b)^n \]  

(3)

where TP is the index of transport capacity, Kc is the combined soil erodibility and cover factor, and the other parameters keep the same meaning as before. Provisionally, exponents m and n have been set to 1 in this specific case. Equation (3) allows to map landscape features as far as relative intensity of the sediment transport capacity is concerned. Equation (3) is thus a pattern model of erosion which does not allow to estimate absolute quantities, but refers to the relative availability of stream power for sediment transport across the landscape.

In addition to the transport capacity index given by equation (3), one can compute the divergence of the pattern TP in the computation domain with planar coordinates (x,y),

\[ \nabla T = d(TP \cos a)/dx + d(TP \sin a)/dy \]  

(4)

where a is the aspect angle of the terrain surface.
The divergence (4) allows to detect the areas where TP increases (excavation/erosion) or decreases (deposition), and the areas where it remains constant. The model represented by equation (4) is referred to as the Unit Stream Power Erosion-Deposition (USPED) model, according to what suggested by the authors (Mitas and Mitasova, 1999).

It is important to stress the difference existing between the indexes computed through equations (3) and (4): the first allows to detect areas with high mass transport capacity, while the second allows to detect the patterns of erosion/deposition. The computation of indexes (3) and (4) is straightforward using elementary map calculations with unit geographic information science (GIS) operations such as slope, aspect, flow direction and contributing area in a grid-cell representation of the topographic surface.

2.3 The database and model results

The RRBA has implemented models (3) and (4) at the scale of the landscape for the whole region. The database which has been used includes:

- a digital terrain model (DTM) obtained through a Triangulated irregular network (TIN) interpolation of topographic data digitised by the Regione Emilia Romagna from the maps at the scale of 1:5,000 available since the 70’s;

- the soil classification map at the scale of 1:250,000, from which an erodibility factor K according to the USLE model [Wischmeier and Smith, 1978] has been computed in the form of a weighted average of the K estimate from point texture data for each soil type in the cartographic unit provided by the Soil Survey Office of the Regione Emilia Romagna [2001];

- a land use map at the scale of 1:25,000, for which a reclassification of the land use classes in terms of C factor has been performed. The soil cover factors used in the study are taken from the literature and reported in Table 1.

A map for both indicators has been produced for the whole area of interest (about 2,000 km²). Equations (3) and (4) thus allow to map the pattern of transport capacity (figure 2) and the areas of net erosion as opposed to the ones of stable or depositional soil processes (figure 3).

Table 1. C factor values used to describe the soil cover effect according to the land use map classes, assigned from literature data [ERSO, 1990]

<table>
<thead>
<tr>
<th>Land Use Class</th>
<th>C-factor [dimensionless]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Croplands</td>
<td>0.100</td>
</tr>
<tr>
<td>Vineyards (not grassed)</td>
<td>0.451</td>
</tr>
<tr>
<td>Orchards (not grassed)</td>
<td>0.296</td>
</tr>
<tr>
<td>Mixed Orchards and Vineyards</td>
<td>0.374</td>
</tr>
<tr>
<td>Chestnut woods</td>
<td>0.002</td>
</tr>
<tr>
<td>Prairies</td>
<td>0.003</td>
</tr>
<tr>
<td>Oak and beech woods</td>
<td>0.003</td>
</tr>
<tr>
<td>Conifer woods</td>
<td>0.001</td>
</tr>
<tr>
<td>Mixed woods</td>
<td>0.002</td>
</tr>
<tr>
<td>Bushlands</td>
<td>0.040</td>
</tr>
<tr>
<td>Recently forested land</td>
<td>0.006</td>
</tr>
<tr>
<td>Heterogeneous agricultural land</td>
<td>0.050</td>
</tr>
</tbody>
</table>

Figure 2. Transport capacity indicator according to equation (3). The TP index increases according to the grey tone scale; the boundaries of the cartographic units for K and C are represented in black; the grey polygon on the right of the image is an area not covered with information on the K-factor.
Figure 3. net erosion pattern according to equation (4). Net erosion corresponds to dark tones.

As it can be noticed, the model capitalizes on both coarse (the soil map) and intermediate (land use map) information, at the same time finely detailing local situations and processes thanks to the detailed DTM which allows landscape interpretation. The patterns of erosion which result from the model look very intuitive and a preliminary field testing has produced encouraging results.

2.4 Some soil management considerations

The model above presented, set up for the area of interest, allows to predict the patterns of soil erosion which can be used as a guideline for soil conservation practices in the areas more prone to soil loss. It must be stressed that soil erosion is a primary issue in basin master planning since hydrological responses of agricultural land are a major factor of hydrogeological hazard.

Soil conservation practices can be evaluated using the P-factor as suggested by the RUSLE [Foster et al. 1997]. Alternatively, one can use more physically based methods to evaluate the required soil conservation practices given a soil type, land cover and topography. In the following, some physically-based considerations on the potential regulatory use of the maps produced are proposed.

If we assume that the maximum shear stress tolerated by a soil type is \( t_{\text{max}} \), the maximum water depth along a hillslope with that soil type during runoff is [Morgan, 1995]:

\[
h_{\text{max}} = \frac{t_{\text{max}}}{\gamma}
\]

where \( \gamma \) is the unit weight of water.

In addition, \( t_{\text{max}} \) can be related to the maximum runoff discharge per unit slope width tolerated by the soil, using Gauckler-Strickler’s formula:

\[
q_{\text{max}} = \left(\frac{t_{\text{max}}}{\gamma}\right)^{\frac{1}{67}} J^{0.5} k_s
\]

and, if we assume that runoff occurs according to the kinematic wave model [e.g. Beven, 2001], the following relation also holds:

\[
q_{\text{max}} = I \varphi A_{\text{max}} / B
\]

In the above expressions, \( J \) is local slope, \( k_s \) is the Gauckler-Strickler roughness coefficient (\( k_s = 1/n \), where \( n \) is Manning’s coefficient), \( A_{\text{max}} \) is the maximum upslope contributing area which is tolerated by the soil given a precipitation intensity \( I \) with a runoff coefficient \( \varphi \), and \( B \) is the slope width. When referring to a grid cell representation of the topography, \( B \) is the cell size.

If we assume that the contributing area \( A \) is a linear function of the upslope flow length \( L \) (which is a common assumption in the rational method when peak runoff is computed assuming as critical the rainfall of duration equal to the time of concentration – see e.g. Maione [1995]), then the reduction in upslope flow length required for the soil to be stable with given precipitation intensity \( I \) is:

\[
L - D = \frac{(A - A_{\text{max}})}{A}
\]

Using equation (9) one can draw up prescriptions for mechanical soil conservation practices and especially for transversal drainage density required along a slope.

Other conservation practices may affect the coefficients \( k_s \), \( \varphi \), and \( t_{\text{max}}/\gamma \). For example, one may refer to the reference manual of physically based models such as EUROSEM [Morgan et al., 1998]. Finally, the following formula holds:

\[
D \varphi \left(\frac{t_{\text{max}}}{\gamma}\right)^{\frac{1}{67}} = (L B / I^1 A^{1.17})
\]
which relates in a physically based fashion the soil management variables with the topographic ones, which are known, for a given design storm of intensity $I$. Thus for example one can decide to increase the distance $D$ at the same time increasing the shear resistance of the soil (e.g. through increasing the organic matter content of the soil), or varying the surface conditions ($\varphi$ and $n$) consequently.

Usually, regulations define transversal drainage density requirements for soil conservation on the basis of classes of slope steepness or similar simplified criteria. According to the approach to soil erosion hazard as above proposed, instead, one can account for the whole set of factors determining erosion in order to calculate the required maximum admissible distance between slope interruptions, $D$. In principle, given the hydrologic and soil parameters used in equation (9) it is possible to calculate $D$ exactly in each site-specific situation. However, due to the difficulty of mapping all the factors in equation (9) with the required detail, it is advisable to calculate $D$ in a few known situations, and then re-scale the prescription on $D$ using equation (3) only in the areas where the divergence (4) assumes positive values.

In principle, this can be done by plotting $D$ values versus $TP$ values, and fitting a regression curve by which to prescribe the required $D$ at each $TP$ value. With such a procedure, the planner is requested to map areas where a constant $D$ is prescribed and the land owners do not have to worry about determining the parameters of their fields from which $D$ is to be computed. This is expected to bring a simplification in managing regulations on agricultural practices, although requiring a more detailed soil erosion analysis at the planning stage.

3. SOME ADDITIONAL REMARKS ON SLOPE INSTABILITY PHENOMENA AND SOIL EROSION

The analysis previously described refers to soil erosion due to runoff. The dual problem concerned with runoff is slope instability due to infiltrating water. The model SHALSTAB [Dietrich and Montgomery, 1998] allows to map potential slope instability as a function of topographic variables (slope and contributing area) in dependence of the parameter $I/(1-\varphi)/T$ where $T$ is the equivalent transmissivity of the slope, and $I/(1-\varphi)$ represents the rate of infiltrating rainfall. The kind of mass movements predicted by this model is the one of shallow landslides, which are those most frequently associated with agricultural operation.

The model is based on the assumption of validity of the infinite slope formula and steady state hydrological response of the slope. Further details can be found in the reference cited. The relation which gives the critical $q/T$ ratio above which instability occurs is:

$$q/T = (\rho_s/\rho_w) \left(1-\tan \alpha / \tan \varphi \right)B/A \sin \alpha$$

where $\rho_s$ and $\rho_w$ are the bulk density of soil and water respectively, $\alpha$ is the slope angle, and $\varphi$ is the friction angle of the soil.

As one can observe from equation (11), the slope instability prediction depends weakly on soil bulk density and more significantly on the friction angle. Thus one can draw a prediction of slope instability in terms of the relative amount of water $q/T$ required to trigger the landslide, given the soil friction angle.

In figure 4 an example of the prediction is shown with the superposition of known landslides and badlands.

It must be stressed that some land management practices, although allowing to reduce soil erosion, may cause slope instability due to the increase in $q=\varphi I$. However, it is important to keep in mind that precipitation events that are critical to soil erosion, i.e. those with highest rainfall intensity, are generally not the ones that trigger landslides (i.e. those of longest duration). Using both the landslide hazard and the soil erosion hazard predictions exposed before, it is expected that good land management practices are being defined.

4. CONCLUSIONS AND FUTURE LINES OF RESEARCH

The approach here discussed allows to keep a physically meaningful control on the effects of different land management scenarios on landscape-scale processes. The RRBA in presently involved in field validation of the model and in the use of its predictions for soil management regulations according to the procedure sketched in section 2.4.

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used in the work and for helpful critical discussion. The Cartographic Office of the Regione Emilia Romagna is also greatly acknowledged for providing topographical data used to build the digital terrain model which forms the basis of the analyses hereby presented.

![Figure 4](image_url)

**Figure 4.** Slope instability index q/T according to equation (11), computed with a friction angle of 25° and a bulk density of the soil of 1.7 t/m³. Instability increases with dark tones. In the figure, boundaries of known landslides and badlands are also shown.

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