Small-scale experiments on soil roughness evolution and first applications to soil erosion risk assessment

F. Catani, S. Menci & S. Moretti
Department of Earth Sciences, University of Florence, Italy

Abstract

This paper presents experimental data on the geometric and morphometric evolution of small scale soil parcels after simulated cycles of rainfall with the aim to contribute to the understanding of soil roughness dynamics. Furthermore we will show some results on erosion modelling and radar remote sensing application related to soil roughness.

Starting from chosen parcels on crops or bare soils, rainfall simulations have been undertaken over repeated cycles of storms in the Chianti region (central Italy). At the beginning of experiments and after each event, a high resolution DEM of the parcel was automatically generated by means of a recently developed digital stereo-photogrammetric ground-based technique. At the same time, sediment yield and runoff were measured.

Initial topographies could basically be considered as random space functions with quasi-isotropic distribution of the micro-relief.

In a second phase, the DEMs have been reciprocally compared and elaborated to produce an evolutionary sequence of small scale relief which has been studied and analysed in order to show how the experimental data can be explained in terms of roughness and landscape evolution.

The results of the study were subsequently used to calibrate remote sensed radar data derived from SAR Shuttle missions in order to include the roughness parameter in the backscattering models.

At the same time the computed roughness was used to derive the friction coefficient $f$ in interrill areas for the application of hydrological-erosive models to assess the soil erosion risk in the area.

Keywords: soil roughness, erosion modelling, radar remote sensing, stereo-photogrammetric ground based technique, sediment yield.
1 Introduction: the photogrammetric technique

The proposed methodology is based on the representation of the studied area in a digital stereoscopic model realised with a fully automatic procedure by means of a special device, developed for the purpose. The hardware portion of the device consists of a double digital camera (fig. 1) exactly self-referenced and reciprocally calibrated mounted on a rigid platform, while the whole instrument is placed on a tripod. This ensures that no base points are required on the ground if not to connect different stereo-models with the same coordinate system: a few visual targets on the ground are sufficient for this purpose and the determination of the digital stereo-models as well as their interconnection and linkage are automatically performed by the software portion of the system. Once the model is ready, the determination of single points can be carried out manually by an operator or automatically by a system to produce a regular grid or DTM. This simple photographic technique can be considered very fast compared to the laser profilometer method while producing a similar accurate DTM.

Figure 1: The double digital camera used and calibrated for the experiments.

First experimental tests have been carried out to evaluate the method precision in planimetry (fig. 2a and b) and in elevation (fig 2c and d). Stereoscopic images have been taken from a chessboard panel (255 by 195 mm) for planimetric precision determination (about 0.5 mm) and from a special 3D-target 20 cm square plate for elevation determination (about 1 mm).
Figure 2: Calibration of the double camera in planimetry (a and b) by subsequent modifications of instrument base, and in elevation (c and d) by subsequent modifications of focal length.

The principal advantages of the mentioned method are outlined as follows:

1. It is not destructive and not invasive, allowing replications of measurements without any contact with the target surface.

2. The photographic record of the surface is preserved indefinitely and can be used for further multitemporal elaborations because of the possibility of surface points to be accurately monitored in changes through time.

3. The technique permits accurate measurements in all three spatial dimensions allowing for the constraints imposed by image quality.

4. The data are captured in digital form and can therefore easily be transferred between Geographical Information System (GIS).

2 Test area

The site chosen for testing the methodology applied in this work is the Chianti region, located on the Tyrrhenian side of the northern Apennine in Tuscany: this area is representative of lithological, climatic, vegetational and land-use conditions common to wider agricultural areas in Tuscany.
As a typically Mediterranean region, the studied area is characterised by an arid period during summer and high rainfall intensities in autumn, decreasing in winter.

2.1 Methods

For the development of experiments, a representative soil was selected with climatic and morphologic condition such that it was widely interactive with the simulated rain.

![Example of a parcel of bare soil used for experiments.](image)

In order to this requirement some vineyards were selected, that is the most valuable cultivation in Tuscany, with the olive trees.

Allotments presented a light slope (about 5%), such to allow a hypothetic flow. The summer period proved the suitable to experiments, so they have carried out during June 2002, when it was possible working in absence of rain, and soil was perfectly dry, because of the last rain was a few months before. Soil was bare, because of the weather and of previous tillage, without centmetric and decimetric particles, specially removed.

Before the beginning of simulations parcels were smoothed and levelled, deleting possible pre-existent micro-relief organisations and every internal flow rill, letting this exclusively to hydrological factor. In general the initially topography presented random elevation distribution.

2.2 Data acquisition

To study erosion processes and to analyse the effects of different rainfall with respect to infiltration capacity, runoff and soil detachment, a field rain simulator was used, fig 4.
Canuti et al. found that infiltration was determined as the difference between the amount of rainfall and the measured amount of runoff [1].

The rain simulator is a portable instrument with variable rain intensity. It is made up of a sprayer which oscillates with variable period Canuti et al.[1]. These operating conditions make it possible to change rainfall conditions during the experiment to give better simulation of natural intensity distribution. However, for the present study, the rain has been maintained constant for an hour to avoid excessive variables. A multiple-intensity rainfall simulator consisting of intermittent oscillation was mounted above 600 by 600 mm crop soil parcels (fig.4).
Table 1: Mean of hydrological erosive results of studied parcels.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Rain intensity (mm/h)</th>
<th>Rain length (minutes)</th>
<th>Return time (years)</th>
<th>Runoff (l)</th>
<th>Sediment yield (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>12.3</td>
<td>20</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>12.3</td>
<td>60</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>34.8</td>
<td>60</td>
<td>10</td>
<td>8.56</td>
<td>153.02</td>
</tr>
<tr>
<td>5</td>
<td>49.7</td>
<td>15</td>
<td>60</td>
<td>3.30</td>
<td>62.50</td>
</tr>
</tbody>
</table>

Figure 6: Evolution of roughness and microtopography outlined by the sequence of DTMs for a parcel.

Figure 7: Example of hydrological erosive balance related to phase 4 for an analysed parcel.

Rainfall intensities have been selected on the basis of return times of 1, 10 and 60 years, with corresponding rainfall intensities of 12.3 mm/h; 34.8 mm/h and 49.7 mm/h (Gumbel distribution, fig. 5).

Each experiment has been split into 5 phases (Table 1) with increasing rainfall intensity and from each phase a DTM has been generated by the proposed methodology obtaining a sequence of DTMs as shown in fig 6.

As shown in table 1, only during the fourth and the fifth simulations runoff and sediment delivery have been generated and measured by filtering samples of mud sorting out the simulator, while at the beginning of experiments (phases 1, 2 and 3) rain intensity resulted clearly too low and soil condition too much dry.

Figure 6 and 7 show erosive balance graphic for 4 and 5 phases.
Table 2: Roughness statistics obtained from DTMs.

<table>
<thead>
<tr>
<th>phase</th>
<th>$\sigma$ (mm)</th>
<th>$\bar{D}$ (-)</th>
<th>$\bar{sr}$ (-)</th>
<th>Range (mm)</th>
<th>Sill (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11,01</td>
<td>2,035</td>
<td>1,19</td>
<td>348,7</td>
<td>136,7</td>
</tr>
<tr>
<td>2</td>
<td>11,23</td>
<td>2,052</td>
<td>1,30</td>
<td>342,3</td>
<td>129,9</td>
</tr>
<tr>
<td>3</td>
<td>11,42</td>
<td>2,029</td>
<td>1,16</td>
<td>347,8</td>
<td>146,9</td>
</tr>
<tr>
<td>4</td>
<td>9,88</td>
<td>2,022</td>
<td>1,13</td>
<td>353,4</td>
<td>102,5</td>
</tr>
<tr>
<td>5</td>
<td>9,59</td>
<td>2,033</td>
<td>1,21</td>
<td>351,6</td>
<td>99,3</td>
</tr>
</tbody>
</table>

Figure 8: Example of hydrological erosive balance related to phase 5 for an analysed parcel.

Table 3: Morphometric evolution statistics obtained from DTMs.

<table>
<thead>
<tr>
<th>phase</th>
<th>$\bar{\theta}$ (°)</th>
<th>$\bar{R}$ (-)</th>
<th>dren.sup (mm²)</th>
<th>max length (mm)</th>
<th>Dren.density (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7,97</td>
<td>1,3E-07</td>
<td>655,89</td>
<td>284,41</td>
<td>4,62</td>
</tr>
<tr>
<td>2</td>
<td>6,10</td>
<td>1,0E-07</td>
<td>604,81</td>
<td>104,98</td>
<td>4,66</td>
</tr>
<tr>
<td>3</td>
<td>9,29</td>
<td>1,5E-07</td>
<td>654,33</td>
<td>133,09</td>
<td>4,54</td>
</tr>
<tr>
<td>4</td>
<td>7,56</td>
<td>1,2E-07</td>
<td>488,08</td>
<td>204,86</td>
<td>5,32</td>
</tr>
<tr>
<td>5</td>
<td>8,64</td>
<td>1,3E-07</td>
<td>639,56</td>
<td>135,27</td>
<td>4,26</td>
</tr>
</tbody>
</table>

Observing figures 6 and 7, the runoff increases with the sediment delivery from phase 4 to 5 because of the major rain intensity and saturation soil level.

3 Data analyses

The obtained DTMs (fig. 6) have a planimetric definition of 0.5mm while their elevation resolution is of about 1mm. These DTMs can be used to characterize the soil roughness and the evolution of micro-scale relief by several methods that are more reliable than single profile 1-D techniques. Table 2 and 3 summarize the preliminary statistics obtained for a series of rainfall simulations.

Relief and soil roughness have been computed by classical methods: the standard deviation of elevation ($\sigma$), the mean of elevation, the Melton’s number...
(ΔH/L, relief parcel length ratio), the mean flow direction (θ), the mean resultant length ℓ and by more complex quantities: range and sill of a fitted spherical geostatistical model, the surface ratio (2D-area / 3D-area) and the fractal dimension (D) calculated by a three-dimensional ruler method.

3.1 Discussion

These quantities do not show (the only exception being the mean of elevation) a clear trend of simplifying landscape with rainfall.

This can be due to an initial process of channel building that balance the general effect of sediment transfer from the heights to the depressions.

In general the best parameters on roughness description are widely the fractal dimension (D), for invariance scalar property, and standard deviation, (σ) for its large applicability in literature Bechini [2], especially in hydrological-erosive models.

Hydrological results show that for a completely dry soil the rain major effect is to disorganise the topography increasing the microrelief. However, subsequent and final trend, is the erosion and the sediment delivery, such that avoid an organised and hierarchised drainage network development. In fact splash erosion, in small parcels, aims to prevail on rill network, creating a rather flat morphology.

4 The WEPP model

4.1 Introduction

Many models are available for the study of soil erosion problems Engman[3]; however, the most suitable model allowing the use of remote sensing data, and consequently of SAR data, seems to be the WEPP (Water Erosion Prediction Project) model. This model has recently been turned by USDA Laflen, [4] and is now available in the slope and basin version. The WEPP model is very sensitive to roughness data which are explicitly required in management database. The model allows continuous monitoring both in time- it estimates the soil loss at any time interval – and in space- information on sensing data on the quantity of soil removed can be compared, disregarding the problem of surface slope which greatly affects SAR image interpretation.

4.2 Applications of the WEPP model

Here, an example of WEPP application on a slope of Chianti area is performed

Table 4 shows the data obtained both by fields experiments (observed soil loss data of studied parcels) and WEPP applications (computed soil loss data). A rather good correspondence is found only for the runoff; but in general, the comparison of soil loss data obtained with the rainfall intensities shows several discrepancies with respect to the computed data. Consequently a model calibration was performed by changing some empirical soil parameters, like hydraulic conductibility and interrill erodibility, in order to obtain truer values.
Table 4: Computed and observed soil loss data in a sample parcel before WEPP calibration.

<table>
<thead>
<tr>
<th>Intensity (mm/h)</th>
<th>Computed soil loss (t/ha)</th>
<th>Observed soil loss</th>
<th>Computed runoff (mm)</th>
<th>Observed runoff (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>34.8</td>
<td>$0.117 \cdot 10^{-3}$</td>
<td>$0.425 \cdot 10^{-3}$</td>
<td>23.73</td>
<td>23.77</td>
</tr>
<tr>
<td>49.7</td>
<td>$0.053 \cdot 10^{-3}$</td>
<td>$0.173 \cdot 10^{-3}$</td>
<td>7.56</td>
<td>9.13</td>
</tr>
</tbody>
</table>

5 Final remarks

In general it can be affirmed, though, that the photogrammetric method allows for a more robust and replicable control on soil roughness measurements. Undergoing experiments should demonstrate the effect of different soil types and rainfall intensities over longer time intervals and over larger parcels.

The hydrological model gives good results in the assessment of water infiltration and overland flow measurements, as shown by the comparison between fields tests and computed data, even though the field and the computed soil loss results are not clearly related. Furthermore, the employed methodology gives an opportunity to introduce remote sensing data related to geophysical parameters (i.e. soil moisture) into the hydrological models.

References