GIS MODELLING TO ASSESS SOIL VULNERABILITY: LAND MAINTENANCE ACTIONS IN THE TURIN PROVINCE

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ABSTRACT:

The reduction of land maintenance actions has determined a need for awareness about soil conservation issues. The main consequence is an increasing soil loss due to flash flood or similar phenomena. This issue needs a new approach leading to a continuous analysis and monitoring action.
The Province of Turin has developed a Strategic Project about land maintenance through a law by decree (D.G.P 1655-268964/2001), showing the lack of objective planning criteria supporting ordinary maintenance. The Province has then defined different study areas which differ for morphology, hazard and risk factors. The aim of the cooperation between Turin Province and the Faculty of Agriculture has led to a guide-line for planning and acting territorial maintenance.
This paper’s aim is to describe the main steps of the development of the GIS-based methodology for potential hazard/risk assessment and land maintenance, integrating the geomorphologic and landscape ecology approaches. The attention will be focused on two benchmark areas, located in Valle Sacra and in the hillside territory near Turin, characterised by different morphological complexity. The project has moreover evolved with the aim of deepening the knowledge in soil stability monitoring through GIS modelling. Specifically, soil physical structure has been studied by evaluating its aggregate stability. In order to follow a multidisciplinary approach data obtained from the laboratory analysis has been merged with topographical information. The main objective was the study and assessment of different soil dynamics, mainly the relation between vulnerability and vegetation cover.

1. INTRODUCTION

In the last decades the interest for sustainable development of mountain areas (Hurni, 1997) has considerably increased for different reasons. As stated in chapter 13 of AGENDA 21 (1992), mountain regions are a source of biodiversity and environmental resources. At the same time, the population’s decrease generally caused a loss of indigenous knowledge and natural resources conservation, too. The main consequences are soil loss and environmental degradation. These processes deserve immediate action and they require an interdisciplinary approach to the integrated analysis of the ecosystem components (soil, topography, land cover....).
AGENDA 21 (Programme “a”) defines several main goals to achieve about *“Generating and strengthening knowledge about the ecology and sustainable development of mountain ecosystems”* (UNDSA, 1992). Among them there is the building or improvement of geographical and ecological knowledge and management. In this framework, Geographic Information Systems (GIS) play a fundamental role in the management of big amounts of territorial data. In fact, they are widely applied in planning (Kliskey, 1995), both in preliminary analysis and decision making (Joerin & Musy, 2000).

In the past, mountain regions suffered lack of geographical information due to extreme ecological conditions and complex relief morphology. Recently, two different approaches have been developed to model complex landscapes and mountain areas. The first is based on DEM (Digital Elevation Model). It provides a 3D representation of the Earth through a 2D raster support. The second derives from the landscape ecology theory (Forman & Gordon, 1986), describing landscape elements, structures and functions according to holistic models, focusing the attention on energy and matter fluxes through natural open systems.Several organisations at different scale have already recognised this potential and they are carrying on GIS-based management programmes (Halpin, 1993; Koshkariov et al., 1993).
In Italy, the Soil Conservation Department is one of the main duties of Province Administrations.The Province of Turin has developed a Strategic Project about land maintenance through a law by decree (D.G.P 1655-268964/2001), showing the lack of objective planning criteria supporting ordinary maintenance. The Province has then defined several study areas which differ for morphology, hazard and risk factors.
The aim of the cooperation between Turin Province and the Faculty of Agriculture has led to a guide-line for planning and acting territorial maintenance. The project has then evolved in a further experiment with the aim of deepening the knowledge in soil stability monitoring through GIS modelling, and physical indexes from soil survey. According to a multidisciplinary approach data obtained from the laboratory analysis has been integrated with topographical information.
This paper’s aim is to describe the main steps of the development of the GIS-based methodologies for hazard/risk assessment and land maintenance, integrating the DEM and landscape ecology approach. And then the study and assessment of different soil dynamics, mainly the relation between vulnerability and vegetation cover.
The attention will be focused on two of the chosen benchmark areas, characterised by different morphological complexity.

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2. VALLE SACRA CASE STUDY: POTENTIAL HAZARD

The first study area is located in Valle Sacra, in the North-Eastern part of Piedmont (398996.00, 5037353.43 - 393598.21, 5027513.85 UTM-ED50 Zone 32). It covers the Piova watershed (2912 Ha). The altitude range is 370 m above mean sea level (confluence with Orco river) to 2406 m (Mount Verzel). Altitude increases northwards, showing the transition between highlands and steep mountain slopes.

Morphological modelling and ecosystem functionality are strongly affected by land degradation and land cover evolution processes. The main trigger factors of hazard and risk in the area are: complex topography with steep slopes, soil erosion, landslides, slope failures due to extreme meteorological events, frequent fires affecting the evolution of vegetation covers, diffuse settlement. Forest fires are typical of winter season, when fire behaviour is influenced by foehn, a katabatic wind blowing down the Alps, heating air as it comes under greater atmospheric pressure, creating strong gusty warm and dry winds.

River dynamics are influenced by hydraulic geometry as altered profiles, narrow cross sections and vegetation growth in riverbed can modify Manning's coefficient, influencing energy loss in water flow. These phenomena commonly cause flash floods due to extreme storm events.

Moreover, the socio-economical marginality of the area has determined a general lack of territorial maintenance. Anyway, the valley is characterised by a high settlement density that requires adequate emergency management.

This reason, together with high heterogeneity of hazard and risk factors, led to the choice of this study area.

Existing base maps, as required by the project partners, have been to obtain derived maps for the following GIS-based analysis .All the classification processes have followed a 5 classes subdivision (Lorito et al., 2003), in order to define critical values, with a minimum of 1 and a maximum of 5.

2.1 Topographic maps

Slope class [%]	*Description*
5 [>80]	precipitous
4 [60-80]	very steep
3 [40-60]	steep
2 [20-40]	sloping
1 [0-20]	flat

Table 1. Slope classes (after Hippoliti, 1994)

The Regional Cartographic Service offers maps in raster and vector format. Contour lines with 25 m equidistance have been extracted, by querying vector map layers, to obtain elevation data. The 3D Analyst Extension (ESRI-ArcGIS) computed the DEM with 10 m grid frame the described vector data. The following step was the slope map derivation.

The slope map has then been classified using the Spatial Analyst Extension, following the threshold values proposed by Hippoliti (1994) for forest harvesting., based on extraction methods. Extraction includes forwarding, skidding, snigging and cable logging, which are strongly conditioned by the nature of terrain and consequently can threaten the safety of forest workers.

2.2 Land cover and vegetation maps

Forest cover and other cover types maps (courtesy of IPLA - Forestry and Environment Institute) have been merged in an unique layer; this product was then converted in raster format and reclassified considering forest health conditions, land use and management, forest cover dynamics. The following classification criteria have been adopted:

- high critical level (classes 4-5):
    - debris, nitrophile vegetation cover
    - scarce ground cover ratio
    - abandoned coppice
    - abandoned rural areas
    - afforestation outside the suitable range
- medium critical level (class 3):
    - meadows and grassland
    - woodland
    - fallow land
- low critical level (classes 1-2):
    - highly protective forest covers.

2.3 Geological map

The geological map was scanned and digitized in shape format, then converted into raster format, and reclassified, based on natural hazard records. The study by ARPA - Regional Environmental Protection Agency (1999), about landslide and rockfall events frequency on different geological substrates, has been followed as a guide-line. Therefore highest critical values have been assigned to ancient river sediments, medium to schists, minimum to granite formations.

3. RESULTS AND DISCUSSION

A parametric model has been adopted, summarizing the different factors' critical values (topography, land cover, geology) through map algebra procedures. Then the result has been reclassified into five classes as in the base layers.

The final result is the map in figure 2 (potential hazard index), representing a global hazard index. This kind of information was integrated with field surveys, in order to verify the automatic individuation of potential processes and to identify actual degradation phenomena.

CLASS	AREA [ha]	AREA [%]
5	1161.4	39.9
4	1200.9	41.2
3	461.7	15.9
2	87.6	3.0
1	0.5	<1.0

Table 2. Classes distribution in the study area

The main problems in Alpine valleys are related with lack of forest management and assessment; they are often influenced by lithological and morphological dynamics too.

Class 5 is characterised by landslides and slope failures. There are also several slopes subject to jointed morphology, consequent water infiltration with physical degradation and loss of stability.

In class 4, with extension similar to the previous class, the main hazard are related with four types of vegetation cover: a) burnt areas, with high frequency of forest fires, covered by bracken fern (*Pteridium aquilinum* (L.) Kuhn.), a fire-adapted species, as fire removes competition and creates the soil conditions suitable for its establishment from spores; b) scarcely burnt areas completely invaded by white birch (*Betula pendula* Roth); c) Larch (*Larix decidua* Mill.) afforestation outside the suitable altitude range, in burnt areas, with consequent lack of mechanical stability; d) abandoned chestnut (*Castanea sativa* Mill.) stands.

Due to land abandonment many minor hydraulic arrangements and slope conservation practices show failure and degradation; these conditions are typical of class 3. In the last century the evolution in vegetation cover led to an improvement of slope stability; this phenomena are even more common in class 2, showing an advanced stage of evolution towards climax vegetation (potential natural plant community).

Class 1 covers a small fraction of the study area with limited slope values and moderate stability.

Moreover the whole area is highly populated, even in the upper part of the basin characterised by the above natural hazard. This factor increasing risk condition is a key point in land management and in the attribution of critical values.

Integrating these elements, homogeneous environmental units has been individuated, characterised by similar trigger factors, actual processes and problems. They provide a basis for planning actions in time and space. Units also provide a global evaluation of land critical elements, connected with river dynamics, slope instabilities and erosion processes.

Integrating map algebra results with field surveys data led to the units definition, then to the classification of land maintenance units. Among these, four main categories have been identified:

3.1 conditions and characteristic hydraulic indexes of rivers

Rivers located in the upper part of the basin are often conditioned by debris-flow events, due to extreme precipitations. This may cause intense undercutting. In the lower section there are mainly deep and V-shaped rock riverbeds.

The stream sediment dimension analysis showed high frequency of very coarse material, sometimes including boulders.

From the vegetational point of view, riverbanks are covered by trees with low mechanical stability on scarcely developed soils, characterized by poor organic matter content and litter periodical removal, reducing root penetration and soil aggregation. This may cause tree overturning.

There are frequent lateral erosion phenomena in the whole study area.

High stream velocity and steepness determine sediment transport and consequent deposition in obstructed cross sections (boulders, fallen trees …).

3.2 river crossing tipology and dimensioning

Cross sections survey showed frequent narrowing in hydraulic geometry, limiting flow and sediment transport. Obstructed sections may be a trigger factor for land slides and consequent increase in sediment transport.

The importance of periodical surveys has been underlined, in order to plan the removal of dead trees and sediment deposition due to floods and landslides, restoring the original section geometry.

3.3 tracks and minor roads characteristics and management

Soil stability is conditioned by the management and maintenance of minor roads and forest tracks. The spatial distribution and spread of instability processes is often related with the presence of roads as they influence the surface runoff and modify slope morphology.

Road network can convey surface flow in preferential paths causing rill and gully erosion and also road obstruction; drainage pipes should drain the excess of water. Here periodical cleaning is required to ensure their regular efficiency.

3.4 vegetation cover characteristics

The main vegetation covers involved in instability processes are: chestnut stands, burnt areas and pastures. They may act as trigger factors because they've lost the original protective function against erosion and soil loss.

Chestnut trees are often overmature and attacked by the chestnut blight (*Cryphonectria parasitica* (Murr.) Barr); sometimes they are affected by forest fires, too.

The traditional silvicultural methods were simple coppice and coppice with standards, with single-layer vertical structure.

Such cover types have become ecologically and mechanically vulnerable due to structural characteristics, overmaturity and single-species composition.

Burnt areas show a drastic reduction in shrub cover, regeneration damage and soil aggregates alteration. The increased porosity in canopy cover can increase splash erosion, as the main effect of the canopy is assumed to be absorption of the energy of the falling raindrops.

In abandoned pastures, herbaceous cover grows vertically without any grazing disturbance. Hence graminaceous stems tend to lay down, increasing runoff and reducing water infiltration; in standard conditions grazing and lateral-spread regrowth would keep monocotyledon stems shorter, increasing soil protection.

On the other side, overgrazing can thin herbaceous cover; bare soil is more susceptible to sheet erosion and rilling.

Maintenance actions should restore the protective function of these vegetation covers, enhancing soil conservation and slope stability.

The above elements are the criteria for land maintenance units individuation. Units define the kind of ordinary maintenance action and the corresponding timetable. Each unit is independent of its location, because it's described by critical components and values, characterised by principal instability components and main trigger factors; similar phenomena cause the same event tipology and they deserve homogeneous actions.

The actions are collected in a reference manual containing guide-lines to be applied all over the Province territory.

These criteria allow decision makers to carry out land planning and hazard assessing following a standardised approach.

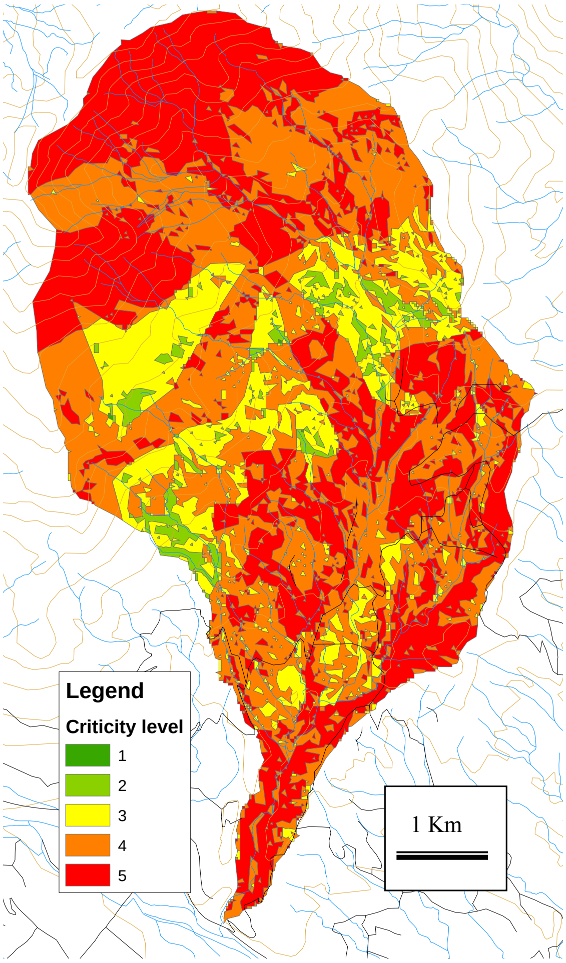


Figure 2. Map of potential hazard index

4. TURIN HILLSIDE CASE STUDY: SOIL VULNERABILITY

The second study area includes nine towns close to Turin (Piemonte, NW Italy, Figure 1). It ranges from 200 m m.s.l. to 670 m m.s.l. with an extension of near 7000 hectares (415797.99; 5003172.61 – 4001159.79; 4992523.70 UTM-ED50 Zone 32).

In order to focus on soil 82 samples (0–15 cm topsoil) located in the whole area have been collected; representing the vegetation cover typologies of the area as described in the regional forest inventory (Camerano et al, 2004) and available in shapefile format in the Region website. These information have been employed in order to plan the sampling location with the purpose of assuring the representativeness of the survey.

WAS (Wet Aggregate Stability) index have then been applied on soil samples in order to assess the soil aggregate stability, i.e. the stability of aggregates in the 1-2 mm diameter range. The aggregate loss was determined after different wet sieving times (5, 10, 15, 20 40 and 60 minutes) using a Yoder sieve apparatus (Yoder, 1936; Pojasok, 1990; Dickson et al. 1991).

The model improved by Zanini et al. (1998) has been adopted, describing aggregate failure with a kinetical approach. Aggregate losses at fixed times are fitted to an exponential model through an iterative procedure:

$$y(x) = b+a(1-e^{-x/c}) \qquad (1)$$

Where:
y = aggregate loss
t= time of wet sieving
b= failure of aggregates for explosion at water saturation
a= maximum estimated abrasion loss
c= parameter linking the rate of breakdown to the abrasion time.

The rate of aggregation breakdown is described by the first derivative:

$$y'(x) = (a/c)e^{-x/c} \qquad (2)$$

As a, b and c, taken individually, are only the expression of a single feature with physical meaning (explosion, abrasion and time of total breakdown), they can not describe the global behaviour of disaggregation processes. In order to reduce the kinetic variability to a single parameter and compare the stability of different vegetation covers, a scalar approach can be carried on. Miller (1980) and Simmons et al. (1979) developed a scaling method applied to aggregate breakdown curves, obtaining a scale mean curve Y*(t) such as that each time series Y_i (t), estimated from measured $y_i(t)$ values, can be represented as a linear function of Y*(t) according to the following relation:

$$\lambda_r Y_i\,(t) = Y^*(t) \qquad (3)$$

where the scale mean time series Y*(t) were derived from

$$1 / Y^*(t) \;=\; \sum_{i=1}^{N} \;[1 / Y_i(t)] \qquad (4)$$

where N is the number of time series.

The scale factor values λ_r were obtained by minimizing the squared misfit

$$\text{misfit} = \sum_t \; \sum_{i=1}^{N} \; [\,\lambda r Y_i(t_i) - Y^*(t_i)]^2 \qquad (5)$$

subject to the constraint $1/N \sum_{i=1}^{N} \lambda_r = 1$. The scale mean curve was computed from the 82 time series using (3) and the scale factors λri derived from a forward Newton iteration using (5).

In order to obtain a spatial information from the sampling points the λ_r values has been interpolated by using an IDW algorithm (Tomeczak M., 2003), generating a raster used in the next phases of the research (Figure 2, on the left).

$$Z_j = \frac{\displaystyle\sum_{i=1}^{n} \frac{Z_i}{\left(h_{ij}+\delta\right)^{\beta}}}{\displaystyle\sum_{i=1}^{n} \frac{1}{\left(h_{ij}+\delta\right)^{\beta}}} \qquad (6)$$

Where:
Z_j = unknown value
Z_i = measured point
β = weighing power
δ = smoothing parameter
h_{ij} = Euclidean distance between the interpolated node j and the contributing data point i.

$$h_{ij} = \sqrt{(\Delta x)^2 + (\Delta y)^2} \qquad (7)$$

Where:

Δx = horizontal distance
Δy = vertical distance

Since soil vulnerability is also affected by geomorphology, the digital terrain model (DTM) of the study area have been computed in raster format with a 25m grid, in order to include this factor in the analysis. Then the LS (Slope-length) factor, which appears in the USLE-RUSLE Equations, describing the effect of topography on soil water erosion, has been calculated, by applying the formula developed by Mitasova et al (1996):

$$LS_{(r)} = (m+1) \cdot \left[\frac{A_{(r)}}{a_0} \right] \cdot m \cdot \left[\frac{\sin b_{(r)}}{b_0} \right] \cdot n \qquad (8)$$

Where:
A[r] = upslope contributing area per unit contour width
b = slope
m, n = empirical parameters
a_0 = 22,1 m. i.e. USLE standard plot length
b_0 = 9%, i.e. USLE standard plot slope
The final result is another raster layer represented in Figure 2 (on the right).
Then every raster computed has been reclassified using a five classes subdivision according to project methodology.
In alternative to empirical approaches such as the USLE-RUSLE methods (Wischmeier and Smith, 1965, 1978) a function based on measured vulnerability data synthesized by the λ_r parameter have been adopted:

$$\text{Vulnerability} = f(\lambda_r;LS) \qquad (9)$$

The function has been developed b aggregating the two rasters using map algebra, and the final result has been classified according to the same criteria as presented in Figure 2.

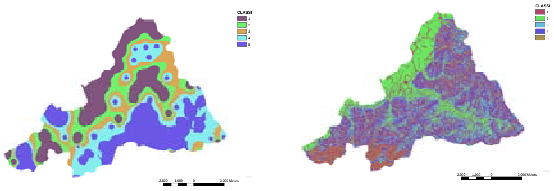
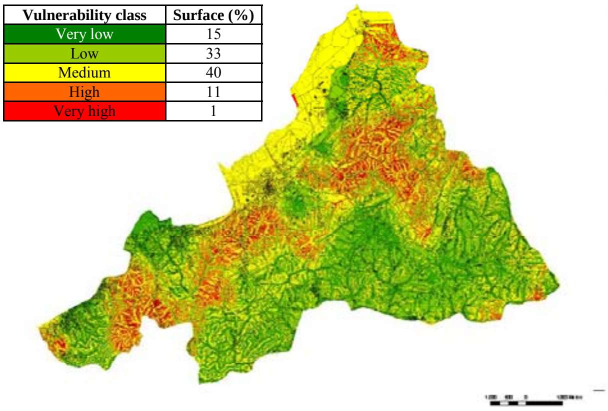


Figure 2. IDW map of λ_r parameter (formula n° 6) and LS factor raster layer (formula n° 8)

5. RESULTS

The vulnerability map (Figure 3) shows the hazard levels with the extension of each class. The “Low” and “Medium” classes prevail in terms of area percentage. The medium class is almost completely represented by flat areas, while scarce vegetation cover plays a role in soil stability affecting the distribution of higher vulnerability values (Zanini et al., 1998). On the other side area affected by high hazard level are located on steep slopes. Since the function includes both vegetation cover and geomorphology, areas with similar topography can show different behaviour, namely a different susceptibility to erosion.



Vulnerability class	Surface (%)
Very low	15
Low	33
Medium	40
High	11
Very high	1

Figure 3. Vulnerability map

6. PROJECT APPLICATION

The described experimental phases have led to the application of the project in the whole Turin Province. Planning, management and field competences have been delegated to “Comunità Montane”, i.e. group of associated municipalities in mountain or hillside areas. Each is responsible for planning and applying maintenance actions on its territory, on watershed basis.
As shown in the next figure, computed from data published in Province’s report (Rossi, 2007) up to the 65% of the basin have their planning phase fulfilled.

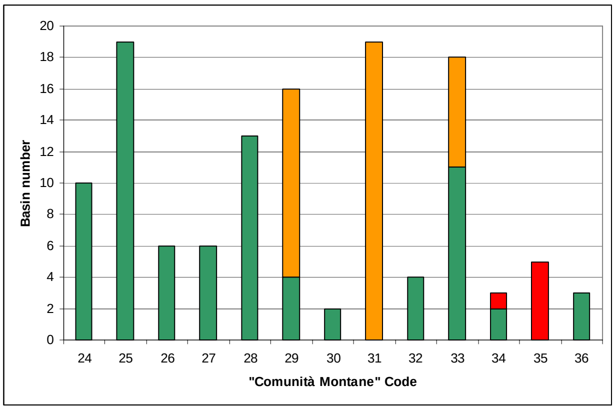


Figure 4. Summary of the planning phase in each “Comunità Montana” (green: completed; orange: work in progress; red: missing)

The following executive phase has been activated in, approximately the 46% of the areas (Figure 5).

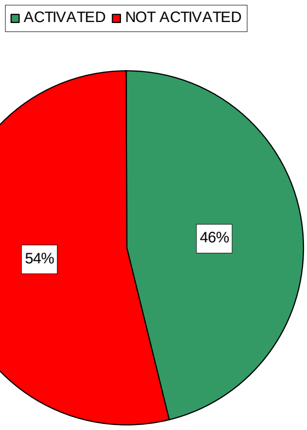


Figure 5. Percentage of "Comunità Montane" which have activated the executive phase

7. CONCLUSIONS

The final results succeeded both in the aim of statistical and cartographical accuracy, providing a synthetic tool for land planners not skilled in GIS or soil science.

Maps are not supposed to describe punctual erosion phenomena, but they allows technicians to point out areas prone to different level of soil vulnerability, in order to plan specific land maintenance strategy and to carry on management actions.

Currently the project has been adopted by the regional government, thus extending its application to the whole territory.

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