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Scientific Report

Application of the WEPP model to evaluate the effect of soil management on the runoff and soil erosion in Mediterranean vineyards

Marcella Biddoccu
Istituto per le Macchine Agricole e Movimento Terra (UOS Torino)
Strada delle Cacce, 73 – 10135 – Torino
m.biddoccu@ima.to.cnr.it

Hosting Istitution:
Institute of Hydraulics and Rural Water Management BOKU - University of Natural Resources and Life Sciences (Vienna).

Supervisor:
Ao.Univ.Prof. DI Dr. Andreas Klik
andreas.klik@boku.ac.at

Introduction

Soil erosion is one of the eight soil degradation processes identified by the European Commission in the "Thematic Strategy for Soil Protection" (CEC, 2006). Although this process occurs naturally, agriculture has increased soil erosion around the world with greater extent until today, with conventional and mechanized agricultural practices that have gradually compromised the soil quality and fertility. Soil erosion directly causes fertility decrease, producing nutrient losses and reducing organic carbon stock. It is frequently related to other degradation processes like soil compaction and low soil water storage capacity. Furthermore the off-site impacts of soil erosion are relevant: water-courses pollution from fertilizers and pesticides, supply of sediments into rivers and reservoirs, and muddy floods (Boardman, 2010) represent the undesirable consequences of the soil erosion process, which role is underestimate among natural hazards.

Cerdan et al. (2010) estimated a mean erosion rate of 2.3 t ha^{-1} $year^{-1}$ for Italy, corresponding to 12.5% of the total European erosion. Measured data showed that in the Mediterranean region the highest runoff rates are related to vineyard land use (Maetens et al., 2012). The soil management practices adopted in hilly vineyards (such as land leveling works during the vineyard plantation, orientation of the vine-rows along the slope, tillage and maintenance of bare soil in the inter-rows) play a primary role in determining high runoff and soil erosion rates (Tropeano, 1984; Ramos and Martinez-Casasnovas, 2006; Blavet et al., 2009). The runoff and soil erosion processes are deeply related to climate, especially to rainfall intensity and precipitation pattern, and the consequent soil moisture content and soil surface conditions.

Evaluation of actual and future erosion rates under a changing climate and land use conditions is a fundamental step in soil and water conservation and environmental planning and assessment. Direct measurements and modeling represent the essential tools available in drawing the present and future soil erosion scenarios.

This report presents the compilation of WEPP data input files and first results of the validation and calibration of the Water Erosion Prediction Project (WEPP) model, in order to evaluate the runoff and soil erosion in sloping vineyards in relation to different soil managements and the climate change issue. Validation and calibration of the model was made by means of the Cannona Data Base (CDB) (Biddoccu et al., *in prep.*). It includes long-term soil and climate dataset (measurements of rainfall, runoff, sediment and soil physical characteristics, and climate parameters), which were collected by IMAMOTER from the Cannona Erosion Plots since 2000. After calibration, WEPP could be applied in order to evaluate the effect of soil management on the runoff and soil erosion in sloping vineyards, in relation with different conservation measures and future climate scenarios.

Material & Methods

Description of the experimental site

The monitored vineyard is part of the "Tenuta Cannona" Experimental Vine and Wine Centre of Regione Piemonte, which is located in the "Alto Monferrato" vine-growing region (Piedmont, NW Italy), at an average elevation of 290 m asl (Fig.1). The climate is temperate, with a mean annual air temperature of 13°C and an average annual precipitation of 875 mm (calculated in the 2000-2011 period). The three experimental vineyard plots were adjacent to each other on a hillslope with SE aspect and average slope of 15%. Soil were classified as *typic Ustorthents, fine-loamy, mixed, calcareous, mesic* (Soil Survey Staff, 2010). Each plot was 1221 m^2 (74 m long and 16,5 m wide), with rows aligned along the slope. During the period of observation, a different cultivation technique was adopted on the soil between the vine rows of each plot: conventional tillage (CT), which was carried out with a chisel at a depth of about 0.25 m; reduced tillage (RT), with a rotary cultivator to a depth of 0.15 m; controlled grass cover (GC), with spontaneous grass controlled by mowing during the year. Tillage and mowing were usually carried out twice a year, in spring and autumn, or in spring and summer. Under the vine-rows of all the three plots, grass was controlled by chemical weeding in spring.

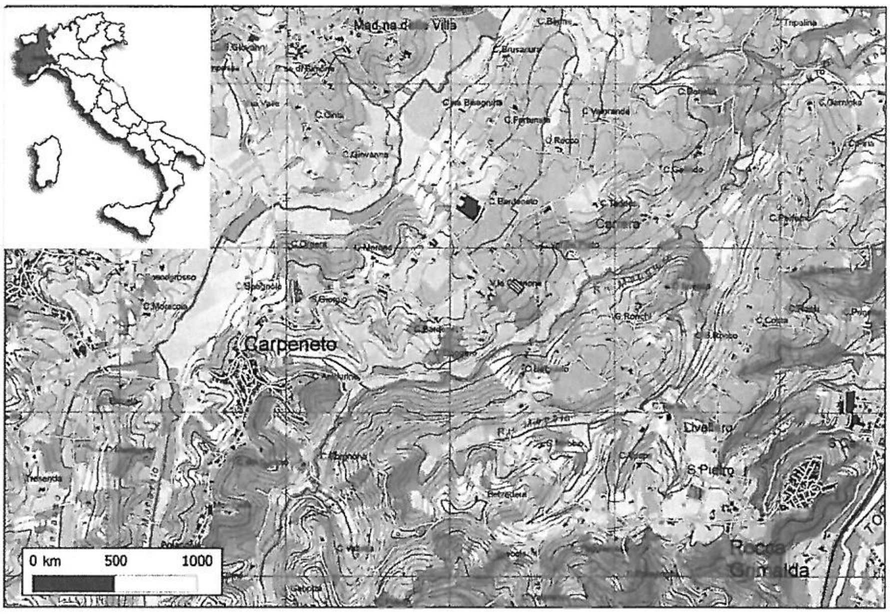


Fig. 1 – Tenuta Cannona Experimental Centre geographic location: red features represent the experimental plots

Each plot was hydraulically bounded. Runoff and sediments were collected at the bottom of each plot by a channel. Each drain was connected to a sedimentation trap and then to a tipping bucket device to measure the runoff discharge. A portion of the runoff-sediment mixture was sent to a sampling tank. From 2000 to 2012, after each rainfall event producing runoff higher than 0.03 mm in every plot, runoff volumes were recorded. A 1.5 L sample of runoff-sediment mixture was collected from each sampling tank, then sediment was oven-dried and weighted in order to determine the mean concentration in the sample and thus the amount of sediment transported by overland flow. Sediments deposited along drains and in the sedimentation traps were collected to obtain the total soil losses due to each event. Hourly rainfall measurements were recorded by a rain-gauge station placed at about 200 m from the plots (Fig.2). Rainfall characteristics were calculated from the data recorded by the rain-gauge for each rainfall event.

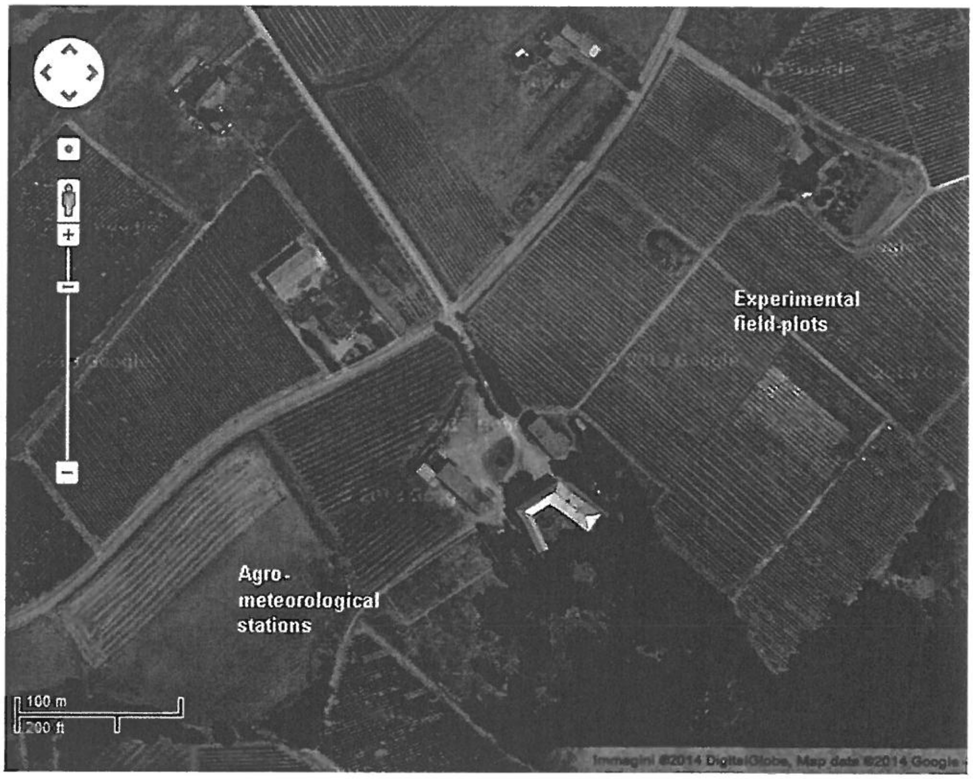


Fig.2 – Aerial view of the Tenuta Cannona Centre. Localization of the experimental field plots (red rectangle) and of the Agro-meteorological stations (blue rectangle).

The WEPP model

The Water Erosion Prediction Project (WEPP) model (Nearing et al., 1989) can simulate the effects of management practices and vegetation to predict erosion at the event scale, as well as at several years scale. The WEPP model is a detailed process-based model, that requires distributed input parameters including data files for climate, slope, soil and cropping/management (Flanagan and Nearing, 1995).

Version 2012.8 of the WEPP model was used in the present study. The model and documentation are available at: http://www.ars.usda.gov/Research/docs.htm?docid=10621.

WEPP was used in its hillslope version, suitable for slopes no longer than 100 m. It could be applied for single events or in continuous simulation mode, which was used in this study case. In the continuous simulation mode, WEPP temporally updates soil, hydrologic and vegetation parameters during the period of simulation. Its basic output contains the runoff and erosion summary information, which may be produced at different temporal basis (from storm-by-storm to annual averages), but further information can be provided (canopy cover, ground cover, soil moisture, and many others).

The CDB offers the possibility to evaluate the seasonal and annual variability of the hydrological and soil erosion processes with the adoption of water/soil conservation measurements, as grass cover maintenance. The dataset is suitable for the validation and calibration procedures at different temporal scales, by means of the available measurements related to climate, slope, soil and cropping/management.

Available data

Long-term runoff and soil erosion data have been collected from differently managed field-scale vineyard plots within the Cannona Erosion Plots. Since 2000 rainfall and runoff gauges have been collected data for each rainfall-runoff event and they are currently in operation. Sediment and nutrient concentrations in collected water have been monitored to permit evaluation of the soil and nutrient losses. During the period of observation surveys have been carried out to investigate spatial and temporal variability of the soil bulk density, soil moisture, penetration resistance. The Cannona Data Base (CDB) includes data for more than 200 runoff events and over 70 soil loss events; moreover, periodic measurements for soil physical characteristics are included for the three plots. The monitoring methods used at the Cannona Erosion Plots and the Database are described in Biddoccu et al. (*in prep*). Available data are summarized in Tab.1. The CDB can soon be accessed via a website (http://sustag.imamoter.cnr.it/) supported by the IMAMOTER-CNR. WEPP input files were compiled on the basis of data included in the CDB.

Tab.1 - Hydrological and soil data available in the Cannona database (Biddoccu et al., in prep.), which were used to compile the WEPP input files.

	Period of data availability	Recurrence of measurement	Data source	Method
Management	2000-2012	n.a.	Farm report	na
Real-time rainfall and runoff (raw data)	2003-present (rainfall) 2011-present (runoff)	daily, hourly	RAM station and runoff gauges	na
Climate (Rainfall and Temperature)	2000-2012	daily, hourly	Tenuta Cannona Centre, RAM and RAN Databases	na
Runoff events	2000-2012	at occurrence	Field measurements (runoff gauges)	Tropeano, 1984
Soil loss events	2000-2012	at occurrence	Runoff water samples and sediment collection	Tropeano, 1984
Texture	1998; 2004; 2012		Field samples	Details in the data file
Chemical	1998; 2012		Field samples	Details in the data file
BD	2004-2006 2009-2012	once/twice year	Field samples	Sample cores (Black and Hartge, 1986)
PR	2004-2006 2009-2012	once/twice year	Field measurements	Static penetrometer (Walczak et al., 1973)
SWC	2004-2006 2009-2012	once/twice year	Field samples	Gravimetric (Black, 1965)
SWC+T -continue	2011-2012	hourly	Field measurements	TDR (Topp et al., 1980)
SWC - profiles	2012	monthly	Field measurements	TDR (Topp et al., 1980)
Topography	2009	-	Topographic survey	Total station

In addition to data of the CDB, soil properties were obtained from the soil map of Regione Piemonte (Regione Piemonte, 2012) and from the atlas of soil of Piedmont (IPLA, 2009).
Additional values for BD and hydraulic conductivity of the topsoil were obtained from field measurements carried out by Biddoccu et al. (2013). Further climate data are available for neighbouring climate stations from the ARPA Meteorological DataBase (ARPA Piemonte, 2013).

Calibration and validation

A sensitivity analysis was carried out to determine which input parameters had most effect on the predictions of runoff and soil loss. Soil parameters that were not available from direct measurements were tested: interrill erodibility (K_i), rill erodibility (K_r), critical shear stress (τ_c), effective hydraulic conductivity (K_e). Sensitivity was analysed using the average linear sensitivity (ALS) approach (Nearing et al., 1990), which expresses a relative normalized change in output to a normalized change in input:

$$\mathrm{ALS} = \frac{\left[\dfrac{O_2 - O_1}{\bar{O}}\right]}{\left[\dfrac{I_2 - I_1}{\bar{I}}\right]}$$

where O_1 and O_2 are the values of the model output obtained with the values of I_1 and I_2 for input parameter I and $\bar{I}$ and $\bar{O}$ are the means of the two input and two output values respectively. This approach is appropriate for comparing the sensitivities of input parameters with values of different orders of magnitude.
The calculation of ALS relies upon the value of all other parameters being held constant (Tab.2) while the value of the parameter under examination is changed. Generally, base values are selected to represent the mid-point of the range likely to be encountered in the field. The range over which each parameter is varied is indicated in Alberts et al. (1995).

Tab.2 - Values used in the average linear sensitivity analysis

			Range	
		base	min	max
K_i	s/m	6377900	500000	12000000
K_r	kg s/m^4	0.011	0.002	0.3
T_c	Pa	4.233	0.3	7
K_b	mm/h	5.34	0.24	24

Following the sensitivity analysis, the calibration and validation process was carried out, using yearly and monthly values. The split-sample technique (Klemes, 1986) was used to evaluate the model in terms of runoff and erosion rates, choosing a three-years period of observation. Following the calibration and validation procedure adopted in olive orchards by Licciardello *et al.* (2013), in the first step, the K_e was modified until the runoff results were as close as possible to the observed runoff values. Then, for the erosion values, interrill erodibility (K_i), rill erodibility (K_r)

and critical shear stress (τ_c) were adjusted one by one. Model performance was evaluated qualitatively, with comparison of the data-display graphics of observed and simulated values, and also using the following quantitative indexes:

Root mean square error $RMSE = \left[\sqrt{\frac{1}{n}\sum_{i=1}^{n}(m_i - p_i)^2}\right]$

Coefficient of efficiency (Nash-Sutcliffe) $NSE = 1 - \frac{\sum_{i=1}^{n}(p_i - m_i)^2}{\sum_{i=1}^{n}(m_i - \bar{m})^2}$

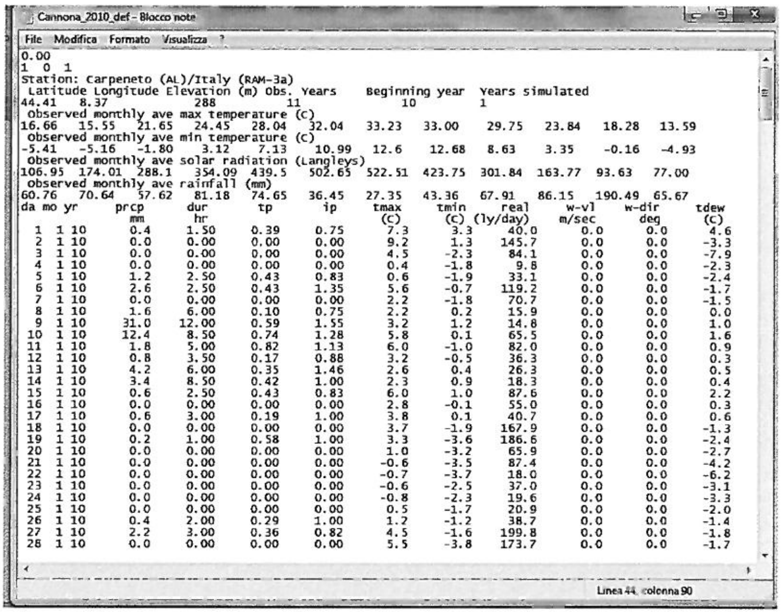
Results and discussion

The input data files

Data from the CDB were collected and used to compile the main WEPP input files:

1. climate file
2. slope file
3. soil file
4. plant/management file

The model requires a large number of parameters. When not available from direct measurements, the values of the WEPP data base were used. For the first phase of calibration/validation, climate and management input file were set up for the period 2010-2012.

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0.00
1  0  1
Station: Carpeneto (AL)/Italy (RAM-3a)
 Latitude Longitude Elevation (m) Obs. Years    Beginning year  Years simulated
44.41    8.37            288           11              10          1
 Observed monthly ave max temperature (C)
16.66   15.55   21.65   24.45   28.04   32.04   33.23   33.00   29.75   23.84   18.28   13.59
 Observed monthly ave min temperature (C)
-5.41   -5.16   -1.80   3.12    7.13    10.99   12.6    12.68   8.63    3.35    -0.16   -4.93
 Observed monthly ave solar radiation (Langleys)
106.95  174.01  288.1   354.09  439.5   502.65  522.51  423.75  301.84  163.77  93.63   77.00
 Observed monthly ave rainfall (mm)
60.76   70.64   57.62   81.18   74.65   36.45   27.35   43.36   67.91   86.15   190.49  65.67
da mo yr      prcp     dur      tp       ip      tmax     tmin    real     w-vl    w-dir     tdew
               mm       hr                        (C)      (C) (ly/day)   m/sec    deg       (C)
  1  1 10      0.4     1.50     0.39     0.75     7.3      3.3     40.0     0.0     0.0      4.6
  2  1 10      0.0     0.00     0.00     0.00     9.2      1.3    145.7     0.0     0.0     -3.3
  3  1 10      0.0     0.00     0.00     0.00     4.5     -2.3     84.1     0.0     0.0     -7.9
  4  1 10      0.0     0.00     0.00     0.00     0.4     -1.8      9.8     0.0     0.0     -2.3
  5  1 10      1.2     2.50     0.43     0.83     0.6     -1.9     33.1     0.0     0.0     -2.4
  6  1 10      2.6     2.50     0.43     1.35     5.6     -0.7    119.2     0.0     0.0     -1.7
  7  1 10      0.0     0.00     0.00     0.00     2.2     -1.8     70.7     0.0     0.0     -1.5
  8  1 10      1.6     6.00     0.10     0.75     2.2      0.2     15.9     0.0     0.0      0.0
  9  1 10     31.0    12.00     0.59     1.55     3.2      1.2     14.8     0.0     0.0      1.0
 10  1 10     12.4     8.50     0.74     1.28     5.8      0.1     65.5     0.0     0.0      1.6
 11  1 10      1.8     5.00     0.82     1.13     6.0     -1.0     82.0     0.0     0.0      0.9
 12  1 10      0.8     3.50     0.17     0.88     3.2     -0.5     36.3     0.0     0.0      0.3
 13  1 10      4.2     6.00     0.35     1.46     2.6      0.4     26.3     0.0     0.0      0.5
 14  1 10      3.4     8.50     0.42     1.00     2.3      0.9     18.3     0.0     0.0      0.4
 15  1 10      0.6     2.50     0.43     0.83     6.0      1.0     87.6     0.0     0.0      2.2
 16  1 10      0.0     0.00     0.00     0.00     2.8     -0.1     55.0     0.0     0.0      0.3
 17  1 10      0.6     3.00     0.19     1.00     3.8      0.1     40.7     0.0     0.0      0.6
 18  1 10      0.0     0.00     0.00     0.00     3.7     -1.9    167.9     0.0     0.0     -1.3
 19  1 10      0.2     1.00     0.58     1.00     3.3     -3.6    186.6     0.0     0.0     -2.4
 20  1 10      0.0     0.00     0.00     0.00     1.0     -3.2     65.9     0.0     0.0     -2.7
 21  1 10      0.0     0.00     0.00     0.00    -0.6     -3.5     87.4     0.0     0.0     -4.2
 22  1 10      0.0     0.00     0.00     0.00    -0.7     -3.7     18.0     0.0     0.0     -6.2
 23  1 10      0.0     0.00     0.00     0.00    -0.6     -2.5     37.0     0.0     0.0     -3.1
 24  1 10      0.0     0.00     0.00     0.00    -0.8     -2.3     19.6     0.0     0.0     -3.3
 25  1 10      0.0     0.00     0.00     0.00     0.5     -1.7     20.9     0.0     0.0     -2.0
 26  1 10      0.4     2.00     0.29     1.00     1.2     -1.2     38.7     0.0     0.0     -1.4
 27  1 10      2.2     3.00     0.36     0.82     4.5     -1.6    199.8     0.0     0.0     -1.8
 28  1 10      0.0     0.00     0.00     0.00     5.5     -3.8    173.7     0.0     0.0     -1.7
```

Fig.3 – WEPP climate file

1. <u>Climate file</u>

The WEPP climate file requires detailed data for precipitation and daily data for minimum and maximum air temperature, solar radiation, dew point temperature, and wind speed/direction (facultative). Data of the Cannona climate stations (RAN and RAM networks) were integrated with data from the ARPA Meteorological Data Base to obtain the complete datasets (Fig.3). Hourly precipitation data were used as input of RIST - Rainfall Intensity Summarization Tool (http://www.ars.usda.gov/Research/docs.htm?docid=3251), that provided precipitation data in the WEPP format, including daily rainfall, storm duration (reduced by excluding periods greater than 30 minutes without rain), *ip* (ratio of the maximum rainfall intensity/average rainfall intensity), and *tp* (ratio of time to rainfall peak/rainfall duration).

2. Slope file

The WEPP model requires information about the hillslope geometry, which is entered by way of the slope input file (Fig.4). Required information includes slope orientation, slope length and slope steepness at point down the profile. Topographical information were obtained from the detailed map of the Cannona Erosion Plots, which was obtained by a topographical survey (available in the CDB).

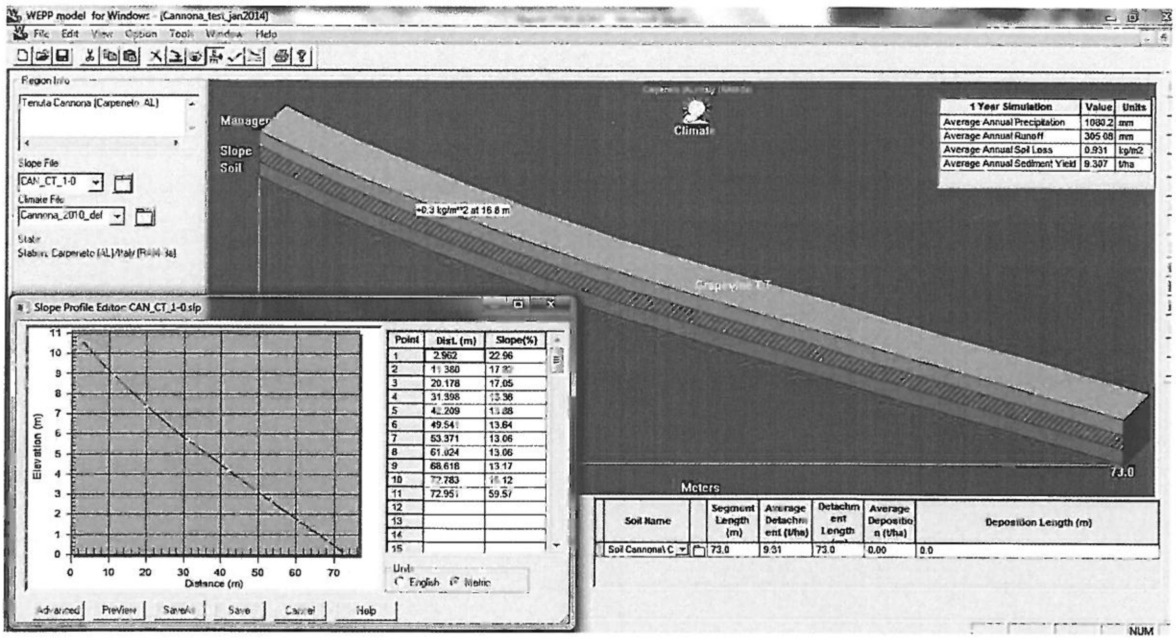

Fig.4 – The Cannona slope file.

3. Soil file

Information on soil properties from topsoil to the bedrock are input to the WEPP model through the soil input file (Fig.5). Information about texture, organic content, CEC and rockiness were provided for different layers. Input data were obtained from the CDB and from IPLA (2009).
Other physical and hydrological parameters are essential for WEPP:

- K_e = effective hydraulic conductivity (mm/h)
- K_i = interrill erodibility (s/m)
- K_r = rill erodibility (kg s/m^4)
- τ_c = critical hydraulic shear (Pa)

The estimation of baseline values for the parameters was done as suggested in the WEPP documentation (Alberts *et al.*, 1995, Flanagan and Nearing, 1995).

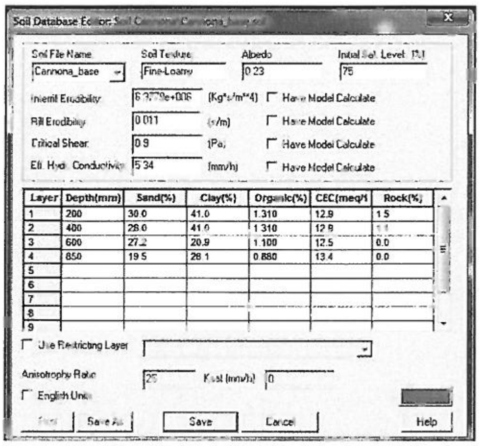

Fig.5 – The Cannona soil file.

4. Plant/management file

The plant/management file (Fig.6) contains all the information needed by the WEPP model related to plant parameters, tillage sequences and tillage implement parameters, plant and residue management, initial conditions. The CDB contains information about the tillage sequences and implementation. Other data for plant parameters were derived from unpublished data, obtained by means of direct measurements. When direct information were not available for the Cannona vineyards (i.e. plant and residue parameters), values from the WEPP data base were used.

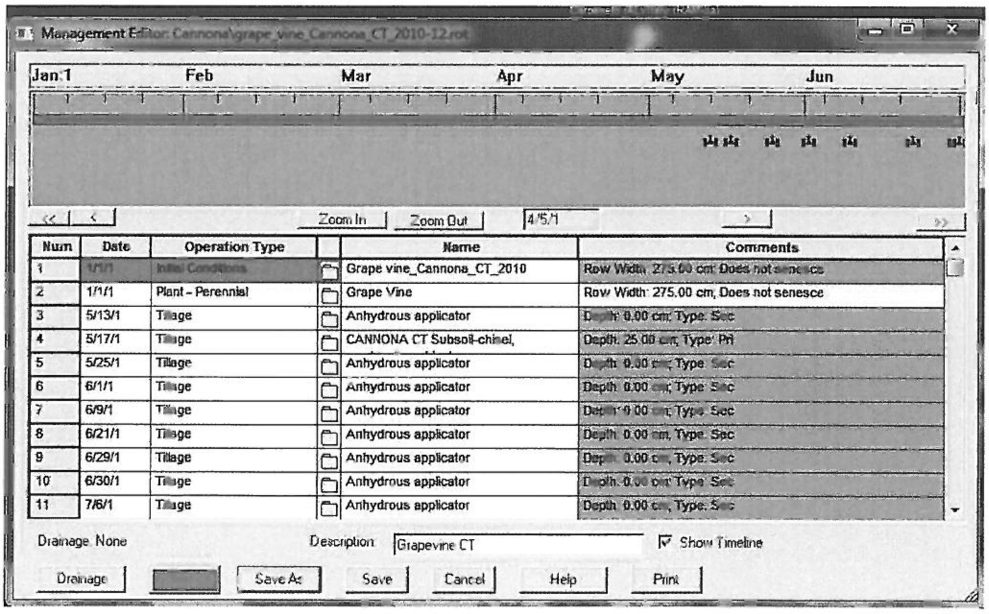

Fig.6 – The Cannona management file.

Run the model: first calibration and validation

Sensitivity analysis

Figure 7 shows the results of the sensitivity analysis for the selected parameters, considering yearly (a) and monthly (b,c) outputs. Runoff is sensitive only to K_e, with higher sensitivity (ALS ≈1) for monthly values than for yearly runoff. Sediment yield is sensitive to all parameters, with higher ALS for K_r and τ_c. Sensitivity to K_i is greater if summer monthly values are considered. The sensitivity to K_e is linked to the runoff sensitivity to this parameter, so it is not possible to change runoff without changes in soil losses.

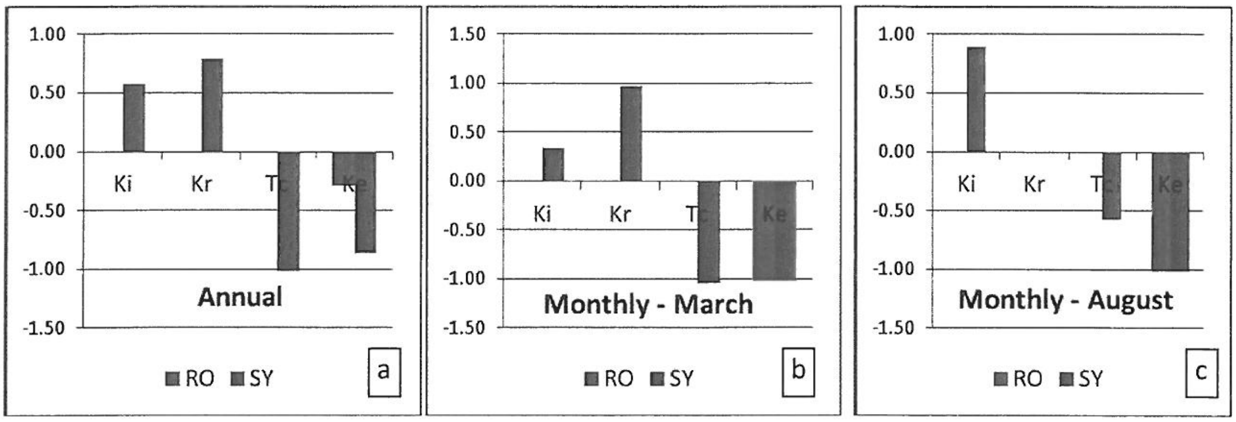

Fig.7 - Values of average linear sensitivity for selected input parameters for (a) annual results and monthly results (b,c).

Calibration and validation

The calibration of the WEPP model was performed considering different values of the "unknown" soil parameters (K_i, K_r, τ_c, K_e). One of the three years of the selected dataset (2010) was used for calibration, adjusting values until the yearly runoff and sediment yields results were as close as possible to the observed values.

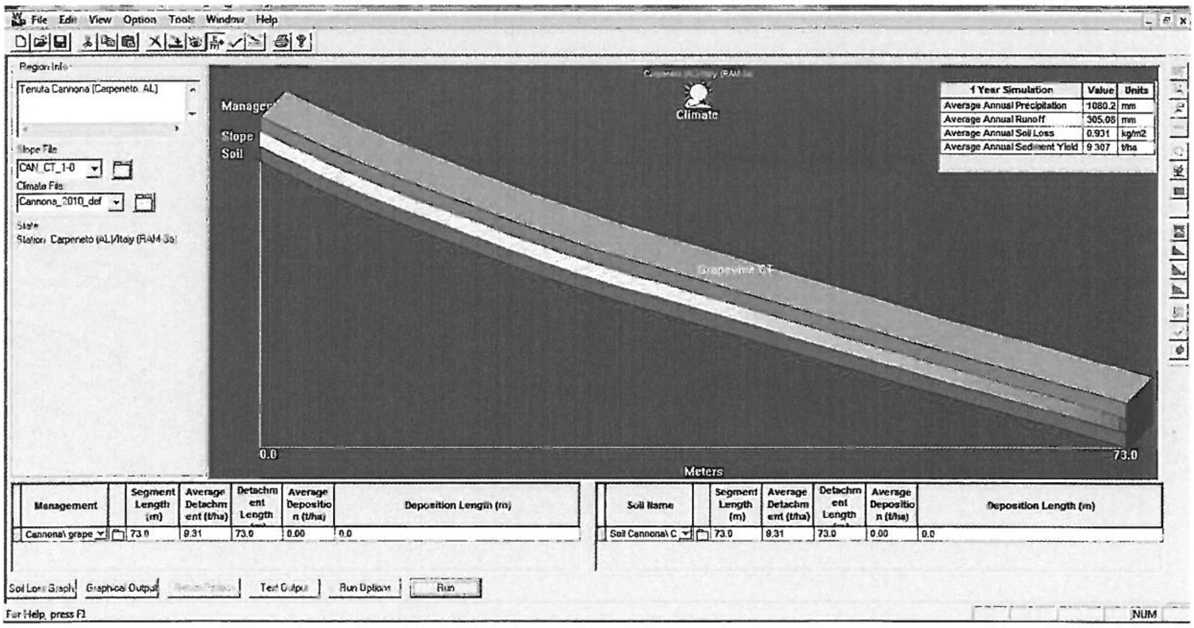

Fig.8 – Image of the "visual" output of WEPP model: colour from white to red in the slope layer shows erosion along the slope.

Tab.3 – Statistics for calibration and validation of the WEPP model during the period 2010-2012 for annual and monthly runoff and sediment yield.

		Annual results				Monthly results			
		RO		SL		RO		SL	
		RMSE (mm)	NSE	RMSE (t/ha)	NSE	RMSE (mm)	NSE	RMSE (t/ha)	NSE
2010	Calib.	6.15	-	0.38	-	28.88	-0.05	2.29	-0.54
2011-2012	Valid.	71.95	0.56	3.28	0.40	-	-	-	-

The monthly values for runoff and sediment yields were also analyzed in order to evaluate the model performance. The calibration with annual data (2011 and 2012) gave good results and acceptable values of RMSE (Tab.3), but the monthly calibration was poor, as the negative values for NSE demonstrated. However the calibrated model gave acceptable results in prediction of the yearly runoff and sediment yields for the two years used for validation (Fig. 9).

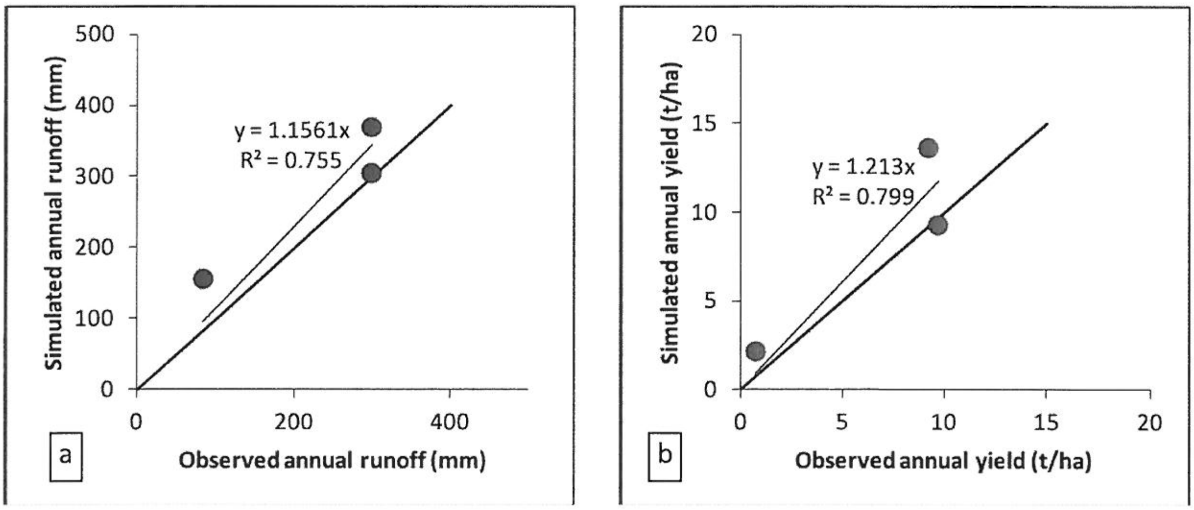

Fig. 9 – Correlation between observed and simulated (a) annual runoff and (b) annual erosion for the selected years.

Conclusions

The Cannona Data Base represents a precious data collection in order to calibrate the WEPP model in vineyards, in order to assess the effect of soil management on the runoff and soil erosion, especially in relation with different conservation measures and future climate scenarios.

The first attempt of calibration, which results were described in this report, resulted to be relatively good for yearly results, as it was demonstrated by results of simulation for the following years. On the contrary, it was not possible to obtain good calibration of the model for monthly results. The poor performance of the model in terms of monthly runoff and soil loss during calibration does not assure a good performance in future simulation.

In order to obtain a better performance of the WEPP model, the calibration and validation procedure must be applied to the Cannona study case using the entire dataset and more detailed precipitation data.

Aknowledgments

The data of the CDB, which were used in this study, were collected at the "Tenuta Cannona Experimental Vine and Wine Centre of Regione Piemonte" within the research projects which were funded by the Office for Agricultural Development of the Piedmont Regional Administration (Projects: "Erosione del suolo: confronto tra inerbimento e diverse modalità di lavorazione del terreno, a rittochino e di traverso" and "Tutela del suolo e delle acque superficiali: confronto ed evoluzione delle caratteristiche del terreno e delle acque di ruscellamento superficiale in vigneti con diversa gestione del suolo e della fertilizzazione", years 2000-2012). I thank the IHLW-BOKU Staff and especially Prof.Klik for willingness in host me and support my research programme.

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