DIGITAL TERRAIN ANALYSIS: DATA SOURCE, RESOLUTION AND APPLICATIONS FOR MODELING PHYSICAL PROCESSES IN AGROECOSYSTEMS

ANALISI DIGITALE DEL TERRITORIO: DATI, RISOLUZIONE ED APPLICAZIONI PER LA MODELLAZIONE DI PROCESSI FISICI IN AGROECOSISTEMI

Bruno Basso[1]

[1]: Department of Cropping Systems, Forestry and Environmental Sciences,University of Basilicata Via Ateno Lucano, 10, Potenza 85100, Italy Tel: +39-0971205386 ; Fax +39-0971-205378 basso@unibas.it;
Adjunct Professer, School of Natural Resource Sciences Queensland University of Technology, Brisbane, Australia

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Abstract
Terrain analysis is the quantitative analysis of topographic surfaces. Most attempts at modeling landscapes have been unsuccessful because the landscape was either looked at in little details or the landscape was considered in two dimensions. The purpose of a digital terrain system is the digital representation of terrain so that environmental problem like soil erosion may be approached accurately and efficiently through automated means.
This paper describes data requirements, methods for storing surface data, advantages, limitations and applications of digital terrain analysis for agriculture and environmental processes modeling. A practical application of the digital terrain model SALUS-TERRAE is presented as case study to simulate spatial variability of soil water content in an agricultural landscape.

Keywords: Digital Terrain Analysis (DTA), Spatial Soil Water Balance, Digital Elevation Model (DEM), Topography; SALUS-TERRAE

Riassunto
L'analisi quantitativa della superficie topografica è detta "terrain analysis". Lo scopo di tale analisi è la rappresentazione digitale del territorio in modo che problemi ambientali come l'erosione del suolo potrebbero essere affrontati in maniera accurata ed efficiente attraverso comandi automatici includendo l'influenza della topografia.
Diversi tentativi di rappresentare i modelli digitali del territorio sono falliti, o perché erano presi in considerazione in piccoli dettagli oppure perché il territorio era considerato in sole due dimensioni. Questo lavoro descrive dati topografici, metodi per la raccolta di dati topografici, vantaggi, limiti ed applicazioni dell'analisi digitale del territorio per la modellazione di processi fisici in agricoltura e ambiente. E' inoltre presentata un'applicazione del modello di analisi territoriale SALUS-TERRAE per la simulazione della variabilità spaziale del contenuto idrico del suolo su scala di campo agricolo..

Parole chiave: *Analisi Digitale del Territorio, Bilancio idrico Spaziale del Terreno, Modello di Elevazione Digitale, Topografia, SALUS-TERRAE*

Rationale

The evolution of modern management techniques has led Three-dimensional data patterns have high information content and can be a powerful vehicle for conveying essential landscape surface information. Terrain analysis is the quantitative analysis of topographic surfaces. Topographic attributes, including specific catchment area, slope, aspect, plan curvature can be calculated and used to predict spatial patterns of soil water content and soil erosion, solar radiation estimation, spatial distribution of soil physical and chemical properties, spatial distribution of vegetation and prediction of vegetation types.
Most attempts at modeling landscapes have been unsuccessful because the landscape was either looked at in little details or the landscape was considered in two dimensions. Basically, digital terrain analysis provides the basis for a wide range of landscape-scale environmental models, which are used for solving research-related problems as well as management decisions.
The objective of this paper is to describe data requirements, methods for storing surface data, and to highlight the advantages and previous limitations of digital terrain analysis for agro-ecosystems modeling. A practical application of the digital terrain model SALUS-TERRAE is presented as case study to simulate spatial variability of soil water content in an agricultural landscape.

Digital Elevation Model
There is a long history of studying landscape surfaces and an abundant knowledge and technology to measure topographic attributes has been developed. A Digital Elevation Model (DEM) is the source of the primary data used as a source of topographic surfaces information alone (Pike, 1988), for landscape modeling (Moore *et al.*, 1991, 1993) as data layers in a GIS (Wiebel and Heller, 1991) and as ancillary data in remote sensing image analysis (Franklin,

1987). In principle, a DEM describes the elevation of any point in a given area in digital format. A discrete representation of a spatially continuous surface is merely a sample of values from the continuous surface. The sample is a finite set of spatial points with definite value (x,y,z) in a given coordinate system. A continuous surface has infinite number of points that could be sampled to precisely represent the surface. Sampling the infinite points of the continuous surface is impractical and unnecessary; indeed a sampling method is used to extract representative points to build a surface model that approximate the actual continuous surface. A discrete sampling set of a continuous surface can still retain the continuity if it is generated from the original surface by following certain sampling procedure. ESRI (1993) stated that a discrete surface model should:

- accurately represent the surface;
- minimize data storage requirements;
- maximize data handling efficiency;

The type of spatial surface dictates the representation and sampling method of the surface. No matter how smooth the landscape surface appears, it is not a mathematical surface, and cannot be represented using a single mathematical function. A landscape surface is a very particular continuous surface which there is no single mathematical function that could be used to describe it. It is a product of the composition of many geological processes (faulting, erosion, sedimentation). Geological young terrains typically have sharp ridges and valleys, in contrast to older terrains which have been smoothed by prolonged exposure to erosional forces (ERSI, 1993).

There are three principal ways used to represent a surface in digital form: contour lines, arrays of equally spaced sample points, and irregularly spaced sample points (ESRI, 1993). The Vector or Contour line model describes the elevation of terrain by contours (stored as Digital Line Graphs, DGLs), the x,y coordinate pairs along each contour of specified elevation. Vector DEMs are based on the most common form of elevation data storage, the topographic map. Topographic maps are prepared directly from aerial photographs or field surveys so the information has undergone the minimum of manipulation, therefore minimizing errors. In the digital contour structure the elevation is recorded only once per contour string. The most popular way to represent a surface is the array of equally spaced sample points. The surface is represented by a "*regular grid*", or matrix, of elevation values. Gridded elevation models can be distributed as simple matrices of elevation, with the location of a single point and the grid spacing, implying the horizontal locations of all other points. Carter (1988) describes the methodologies for the digital representation of topographic surfaces. Topographic surfaces are non-stationary, more specifically, the roughness of the terrain is not periodic but changes from one land type to another. A regular grid therefore has to be adjusted to the roughest terrain in the model and be highly redundant in smooth terrain. It is apparent that, if one has to model these non-stationary surfaces accurately and efficiently, one must use a method that adapts to this variation. In response to this problem the Triangulated Irregular Network (TINs) was created. TINs are based on "coordinate random" but "surface specific" sample points. The location of these model would be dictated solely by the surface being modeled. By "surface specific" it is meant that they would be clustered in those regions of maximum roughness. In its most common form, the TIN is a set of irregularly-spaced points connected into a network of edges that form space-filling, non overlapping triangles. The points are usually connected according to a Delaunay triangulation, a procedure that joins the centers neighboring Thiessen polygons. The facets are usually assumed to planar. The irregular nature of the TIN has many advantages and disadvantages. The primary advantage is variable resolution: a TIN can include many points where the surface is rugged and changing rapidly, but at the same time, only a few points in areas where the surface is relatively uniform. Another significant advantage is the ability to include important surface points (peaks, pits, passes, road and stream intersections, points along ridges and drains) at their exact locations (due to the precision of the coordinate storage). These advantages are countered by complexities in storage and manipulation. Unlike a regular grid which provides an implicit neighborhood through the mechanism of the matrix, a TIN system would have to include this neighborhood explicitly (Peucker *et al.*, 1975). Indeed, the location of every point in a TIN must be specified in the x,y, and z dimensions, as well as the topology of the points (the edges and adjacencies of the triangles). An intensive comparison between these three structures, together with applications of terrain analysis methods based on these structures for calculating topographic attributes and terrain-based indices of a variety of hydrological, geomorphological and biological processes is discussed by Moore *et al.*, (1991a) and Kumler (1994).

Data Source of Digital Elevation Models.

In principle, any data that contains the elevation information with location context can be a DEM data source. Practically, the main source of data for producing the digital elevation model are topographic contour lines, randomly distributed elevation points, the frame points of land surface such as peak, sinks, passes, points of change in slope, ridges, stream channels and shorelines, as well as stereoplotter data (e.g. stereo aerial-photo pair or stereo SPOT image pair) etc. Stereocorrelated DEMs are created from two complementary images, aerial photographs, or satellite images (Schenk, 1989). Raw data in the form of stereo photographs or field survey (the accurate data source) are not readily available to potential end users of a DEM. Therefore, most users must rely on published topographic maps or DEMs produced by government agencies such as the United States Geological Survey (USGS). USGS produces several standard types of DEM data:

- 7.5-minute DEMs have a 30-by-30 meter point spacing in x and y;
- 30-minute DEMs have 2-by-2 arc second point spacing, approximately 60-by-60 meter point spacing in x and y;
- 1-degree DEMs have 3-by-3 arc second point spacing, approximately 100-by-100 meter spacing in x and y.

Spatial resolution and accuracy of digital elevation model.

The distance between two adjacent cells, or the geometric size of a cell or pixel in the x and y horizontal directions is called the spatial resolution of the DEM (or "grain"). The spatial resolution of a DEM is higher than another if its cell size is smaller than another's. Spatial resolution is refined if cell size is decreased, or coarsened, if cell size is increased. Generally, the finer the spatial resolution is, the higher the accuracy of the DEM. The number of cells of a DEM covering a certain area will be increased when increasing the spatial resolution, and vice versa. The spatial resolution is very dependent upon the primary data used to produce the DEM, and the cost of computer storage and processing time.

The optimum spatial resolution of a DEM is closely related to the spatial scale of the of landscape pattern analysis and geo-modeling. For example, when soil properties with broad geographic extent are required, then a DEM with relatively coarse spatial resolution is indicated. To model detailed spatial distribution of soil properties, instead, a fine spatial resolution DEM will be needed. The topographic attributes computed from DEMs are dependent on the resolution of the elevation data from which they are computed. A regular grid is not an ideal representation of topographic surfaces for the study of scale effects. Gallant and Hutchison (1997) pointed out that when we subsample an elevation grid to obtain another grid at coarser resolution, beside the intended change in losing fine scale features of the surface, we also change the number of square cells into which the surface is divided. This is of particular importance when studying a "specific catchment area" that is computed by accumulating cell areas from adjacent cells. Thus, it is important not to confuse scale effect with grid effect if the objective is to study scale properties of a topographic surface. Gallant and Hutchinson (1997) suggested that to appropriately represent a topographic surface for the analysis of scale effects, the size and shape of features should be assessed at different scales.

The accuracy of DEMs in representing the land surface is mainly dependent upon its source data spatial resolution (USGS, 1987). If we build the DEM from contour data that have been captured directly from aerial photographs as primary data using a stereopotter, the contours are highly accurate (ESRI, 1993) and the accuracy of the DEM could be high. However, when the contours have been generated from point data, the accuracy could be lower because contours must be interpolated. A DEM usually uses discrete sampling points with raster structure to represent the relief of the landscape surface. Generally, it is difficult using discrete sampling points to represent every detailed feature and anomaly such as streams, ridges, peaks, and pits. Consequently, the higher the spatial resolution, the more detailed information content the DEM could represent and therefore the more accurate the DEM is. Conversely, a DEM with lower spatial resolution will miss more detailed information of the land surface. With a standard DEM, most terrain features are generalized by being reduced to grid nodes spaced at regular intersections in the horizontal plane. This generalization reduces the ability to recover position of specific features less than the interval spacing. Theoretically, for a given source data set, the only way to enhance the representation of detailed information of the landscape surface is to refine the spatial resolution of the DEM; as the spatial resolution is refined, there is an increasing likelihood that significant features of land surfaces will be represented. Nevertheless, it is not possible for a DEM to obtain more detailed information than that contained in the source data. Hutchinson (1996) shows how DEM resolution can be matched to information content of source data. Moreover, the spatial resolution of a DEM required to contain detailed information of a landscape surface varies with roughness characteristics of natural landscape surface. A rough surface usually needs a DEM with relatively fine resolution, while a coarse spatial resolution will be required by a smooth surface. After selecting the source data at the appropriate scale, the final stage is to interpolate the source data to a grid of elevation points. There are many choices here, and the quality of the DEM is critically dependent on this stage. General-purpose interpolation methods such as Kriging will produce a surface that is reasonably consistent with the data but may contain features such as sinks that are not really present in the real topography. They may also introduce biases that only become apparent when deriving terrain attributes such as slope and aspect for the DEM. The attention to shape and the drainage characteristics of the surface are critical to the production of a high quality DEM. The ANUDEM (Hutchison, 1989) program is widely used and regarded as the best technique available for producing grid DEMs from contour, spot height and stream line data. ANUDEM is based on general-purpose spline interpolation algorithms with a number of special features which make it particularly useful for DEM production. It automatically enforces surface drainage, removing spurious sinks, and adjusts the shape of the surface to agree with stream line data. The program also provides useful diagnostic information for detecting errors in the input data. ANUDEM is available inside ARC/INFO as the topogrid command.

Digital Terrain Modeling

Digital Terrain Models (DTM) have been used in geoscience application since the 1950s (Miller and Laflamme 1958). Since then, they have become a major constituent of geographical information processing. They provide a basis for a great number of applications in the earth and the engineering sciences. In GIS, DTMs provide an opportunity to model, analyze and display phenomena related to topography. Indeed, DTMs include the spatial distribution of terrain attributes. The spatial distribution of topographic attributes can thus be used as a direct or indirect measure of spatial variability of these processes.

Digital terrain modeling encompasses the following general tasks (Weibel and Heller, 1991):

DTM generation: sampling of original terrain data, formation of relations among the diverse observations;

DTM manipulation: modification and refinement of DTMs;

DTM interpretation: DTM analysis, information, extraction from DTMs
DTM application: development of appropriate application model for specific disciplines.

Landscape topographic attributes
Landscape topographic attributes are spatial variables that are used to describe and represent the shape and pattern of the landscape surface. Digital terrain analysis and GIS technology provide tools to quantitatively define landscape attributes.
Speight (1974) described over 20 attributes that can be used to depict landforms. Moore *et al*., (1991b, 1993a) also described terrain attributes and divided them into categories: primary and secondary or compound attributes. Primary attributes are directly calculated from elevation data and include variables such as elevation, slope, aspect, curvature etc.
Secondary or compound attributes involve combinations of the primary attributes and are indices that describe or characterize the spatial variability of specific processes occurring on the landscape such as soil water content or the potential for sheet erosion.

The mathematical representation of most attributes and the methods for calculating them can be found in Moore (1991a, 1993b), ESRI (1993), Gallant and Wilson (1996, 2000).
Topographic attributes can also be divided in local, regional, catchment and process oriented. Local topographic attributes are those that can be calculated from a small neighboring area surrounding the DEM cell using certain algorithm. The neighboring area is usually 3x3 cells. Table 1 gives most of these attributes. The accuracy of the local topographic attributes is closely related to the spatial resolution of the DEM.
Regional topographic attributes are those attributes that are calculated using considerabily larger geometric area than the local topographic attributes (Table 2). The regional topographic attributes are less sensitive to the spatial resolution of the DEM than local topographic.
Catchment oriented topographic attributes (Table 3) are those attributes that are related to the whole catchment area, and are the measurement of certain catchment characteristics. The output value of the attribute at each DEM cell is calculated from certain combinations of all of DEM cells in the catchment. The catchment oriented topographic attributes have very little sensitivity to the spatial resolution of the DEM.
Finally, the process oriented topographic attributes (Table 4) are those attributes that describe or characterize the spatial variability of a simple representation of specific processes that occur on the landscape which can be calculated from the DEM.
Several researchers (Jones, *et al*., 1989; Bell *et al***.**, 1992; Moore *et al*., 1993c; Gessler *et al*.; 1995; Timlin *et al* 1998; Xu, 1999, Kravchencko *et al*, 2000, 2003, 2005; Kitchen *et al*., 2003; Kutcher *et al*., 2005) have found high correlation between changes in these terrain variables and changes in soil drainage characteristics, A horizon depth, organic matter content, extractable-P, pH, sand, silt and soil taxonomic classes and crop yield.

Tab. 1 - Local topographic attributes
Tab. 1 - Attributi topografici locali

Attribute	Definition
Altitude	Elevation above sea level
Slope	Maximum rate of change in elevation from each DEM cell
Aspect	Direction of the maximum rate of change in elevation from each cell DEM
Surface curvature	Measure of the surface convexity or concavity
Profile curvature	Curvature of a surface in the direction of steepest slope
Plan curvature	Curvature of a surface perpendicular to the direction of steepest slope
Tangent curvature	Plan curvature multiplied by the slope

Tab. 2 - Regional topographic attributes
Tab. 2 - Attributi topografici regionali

Attribute	Definition
Upslope area	Catchment area above a short length of contour
Upslope slope	Mean slope of upslope area
Upslope height	Mean height of upslope area
Upslope length	Mean length of flow paths to a point in the catchment
Dispersal area	Area downslope from a short length of contour
Dispersal slope	Mean slope of dispersal area
Dispersal length	Distance from a point in the catchment to the outlet
Flow path length	Maximum distance of water flow to a point in the catchment
Specific catchment area	Upslope area per unit width of contour
Elevation percentile	Ranking of the central point elevation compared to all the points in the surrounding region with a given area radius
Elevation difference	Difference between the central point elevation compared to all the points in the surrounding region with a given area radius
Elevation deviation	Elevation difference scaled by the standard deviation of elevation of the surrounding region with a given area radius
Elevation standard deviation	Standard deviation of the surrounding region with a given area radius
Elevation semi-variance	Two-dimensional semi-variogram of the surrounding region with a given area radius. It is an appropriate measure of the two-dimensional fractal dimension of the region

Tab. 3 - Catchment oriented topographic attributes
Tab. 3 - Attributi topografici a scala di bacino

Attribute	Definition
Catchment area	Area draining to catchment outlet
Catchment slope	Average slope over the catchment
Catchment length	Distance from highest point to catchment outlet

Tab. 4 - Process oriented topographic attributes
***Tab. 4** - Attributi topografici di processi*

Attribute	Definition
Terrain wetness index (TWI)	$TWI = \ln (A_s/\tan\beta)$ where, A_s = upslope area / flow width, β is the slope

Topographic attributes, including specific catchment area, slope, aspect, plan curvature can be calculated and used to predict spatial patterns of soil water content and soil erosion (Beven and Kirkby, 1979; Moore and Wilson, 1992; Moore *et al.*, 1993c; Wilson and Gallant, 1996); solar radiation estimation (Moore *et al.*, 1993; Wilson and Gallant, 1998); spatial distribution of physical and chemical properties of the soil (Moore *et al.*, 1993c; Gessler, *et al.*, 1995); spatial distribution of vegetation (Moore *et al.*, 1993a) and prediction of vegetation types (Brown, 1994).

Terrain-based hydrological modeling

In recent years, considerable progress has been made in the development of computer-based mathematical and computational techniques to model hydrological processes at various scales of analysis. GIS technology has become widely used in hydrological and water quality modeling. Hillslope hydrologists have long assumed that the downslope movement of water can be described by surface topography since gravitational potential largely dominates hydraulic gradients in steep terrains. Hence with the increased availability of DTMs, surface topography is driving many popular hydrological models. Since the first computer-based model hydrologic models were developed in the early 1960's, hydrologists have been attempting to use micro-scale process descriptions in meso-scale (catchment scale) hydrology. The massive computational effort required to solve equations describing processes in three dimensions and the intensive inputs requirement for the physically based model has limited the success of such models. However, computations may be reduced if the dimensions can be reduced from three to two. This concept was first applied by Onstad and Brakensiek (1968) and Onstad (1973). The proposed a flow net of gravitational potential between contours and their orthogonals (lines of steepest slope). Water was routed laterally down strips of land elements defined by this network and they termed this approach "stream path" or "stream tube". Adjacent contour lines and streamlines define irregularly shaped elements. Surface runoff enters an element orthogonal to the upslope contour line and exists orthogonal to the downslope contour line. Flow from one element can then be successively routed to dowslope elements formed by the same stream tube. Moore and Grayson, 1991 adopted this approach in their chatchment partition model: TAPES-C (Topographic Analysis Programs for the Environmental Sciences-Contour. TAPES-C performs the partitioning of the catchement beginning at the contour line of lowest elevation and ending at the highest contour line, successively determining the elements for each adjacent pair of contour lines. TAPES-C has been used for distributed hydrological modeling that accounts for the effect of three dimensional terrain on storm runoff generation. THALES (Grayson *et al.*, 1992) is the hydrologic model that is coupled with TAPES-C. This DTM has two major limitations: the first is that it cannot handle depression for the flow network, thus requires a depressionless DEM, which is not a reality in many agricultural fields. The second limitation is that being the model mechanistic, it requires several inputs that are often not available. Also, there is inconsistency in scale between the measurements of field variables and the way they are applied in the models.

TAPES model has also a grid version, TAPES-G (Gallant and Wilson, 1996). TAPES-G generates primary and secondary attributes from a DEM and it is consider a static model since it does not contains a dynamic water balance model. Through the generation of topographic attributes, TAPES-G has been applied in a variety of environmental modeling applications. In respect to hydrological modeling, flow routing is available in TAPES-G with four different algorithms. Flow is routed from one cell to one and only one of its eight neighbor cells is based on the deepest descent. This algorithm, called D8 produces parallel lines of flow along preferred directions. A second algorithm for flow directions (Rho8) aims to break the up the parallel flow lines by introducing a random disturbance to the flow direction. The Rho8 algorithm is stocastic, indeed produces a different flow network each time it is run. Flow dispersion is introduced in FD8 and FRho8, where the fractional amount of flow dispersed to each of the neighbors depends on the slope from the center cells to the neighbor. TAPES-G also computes the terrain wetness index (TWI), helpful in identifying areas of divergence and convergence based on the slope gradient. Where the slope gradient is low, the soil becomes wetter because the water is not removed to other downslope elements. Moore *et al.*, (1988) found a strong correlation between this index and the distribution of surface soil water content. Gessler *et al.* (1995) found that the index, along with plan curvature, is a fairly good predictor of soil properties (A horizon depth, solum depth).

With a similar approach of TAPES-C, TOPOG, an eco-hydrological model, was develop by CSIRO in Australia to predict plant growth and the three dimensional water and salt balance of heterogeneous catchments. Vertessy *et al.*, 1993 describe the framework of this physically based, distributed parameter catchment model. The models uses Richard's equations for vertical moisture flow, in multi-layered soils, Darcy's Law for for lateral saturated flow, the convection-dispersion equation for solute transport, and evapotranspiration based on the Penman-Monteith model. Soil water extraction is through a distributed root system from the multilayered soil, and there is water exchange with the underlying aquifer system. The model demands significant input data that are costly, time consuming and difficult to measure, so most of the model inputs have to be guessed (Refsgaard *et al*., 1992). Vertessy *et al*., (1993) have used TOPOG to predict water yield from a mountain ash forest. Modelled and observed daily runoff compared well. Over the full period of simulation (12 years) the model overpredicted runoff by less 5%.

Beven and Kirky, (1979) developed an hydrological model called TOPMODEL with the general thinking that variable source areas could be identified and the process of modeling basin hydrology be simplified, by summarizing the saturation potential, based on topographic position.

Several other terrain-based overland flow, runoff and non-point source pollution model have been reported in the literature, including the TIN-based models of Jones *et al*. (1990); grid-based models such as SHE (Abbott el al., 1986), MEDRUSH, Kirky *et al*., (1996), WEPP, Laflen *et al*., 1997, Cochrane and Flanagan, (1999), Wang and Hjelmfelt (1998).

The hydrological models examined in this review were all physically based and such approach has come to scrutiny in recent years (Grayson *et al*., 1992 a, b,). There is a considerable scepticism about their use in hydrology, because the concerns related to the scarsity of appropriate input and validation datasets. Also most of them are based on Richards equations for water flow, that can produce good results for soil evaporation, but it cannot predict plant evaporation as well when the root system is present (Ritchie and Johnson, 1990). The current DTMs cannot handle depression for flow network, thus requiring a depressionless DEM, which is not a reality in many agricultural fields. These DTMs were designed for large-scale applications and for quantifying water quality running into streams, thus the sinks and depressions are filled to have a continuos flow of water down to the streams.

To overcome the limitations mentioned above, a new DTM called TERRAE was developed (Gallant, 1999). TERRAE constructs a network of elements by creating flow lines and contours from a grid DEM. TERRAE can create contours at any elevation in the grid and does not rely on pre-defined contours. Each element created by TERRAE is an irregular polygon with contours as the upper and lower edges and flow lines as the left and right edges. The elements are connected so that the flow out of one element flows into the adjacent downslope element. The element network created by executing TERRAE is used by the spatial soil water balance model, SALUS-TERRAE (Basso, 2000). Surface runoff and subsurface lateral movement is routed from one element to the next starting from the top element and moving downward. The spatial soil water balance model allows the presence of different soil types to a maximum equal to the number of the elements created. The output element attributes include: the element number, the area of the element, the slope of the element and the x, y and z coordinates of the center of the element and the topology (the connections of the elements). The daily loop is initiated by reading the weather information and by calculating the soil water balance for the downward flow for each of the element. The surface runoff produced by each element is moved laterally to the next downslope element. The amount of surface runoff is calculated by multiplying the surface runoff of the upslope element by the area of the element. This amount of water is added onto the next downslope elements as additional precipitation. If there is not a downslope element, the surface water runs off to the field outlet. The downward flow is calculated by introducing a correction factor to account for the slower flow that occurs at the deeper layers. The correction factor consists in separating the saturated hydraulic conductivity (KSAT) variable into a KSAT for the effective vertical flow (KSAT-Vert) and a KSAT for the saturated flow (KSAT-Macro). Details on SALUS-TERRAE are described in Basso (2000), Batchelor *et al*., 2002.

Case Study: application of SALUS-TERRAE to simulate spatial variability of soil water content in an agricultural landscape

Models that consider the dynamics of soil water balance and crop growth have been extensively used to quantify the risk related to the uncertainty in water supply (Ritchie 1991, Jones and Ritchie, 1996, Braga *et al*., 1999). The CERES family models have proven to be effective in simulating the water balance of soils when the drainage is vertical, often an unrealistic assumption. Runoff produced by such models is only from a point in space and there is no account for the water over space and time. To use such models for erosion estimates and for poorly drained soil, sloping terrain, the spatial and temporal relationship between various hydrological processes must be addressed.
Without accounting for the terrain characteristics, accurate prediction of soil water balance is not possible.
The automation of terrain analysis and the use of Digital Elevation Models (DEMs) has made it possible to easily quantify the topographic attributes of the landscape and to use topography as one of the major driving variables for many hydrological models.

The overall hypothesis of this study is that the terrain characteristics and landscape positions control soil physical properties through organic matter accumulation, formation of soil horizons and soil structure that highly influence the soil water balance. Landscape position also determines how much precipitation infiltrates into the soil profile and for how long water can pond on the surface, as well as how much water can pond before it infiltrates or runs off to other areas in the landscape. In this study, it is also hypothesized that the partitioning between vertical and lateral movement at a field-scale level will help us to better predict the complete soil water balance and consequently the available water for the plants over space and time.

The study evaluated the capability of SALUS-TERRAE applied at field scale with rolling terrain to simulate spatial variability of soil water content.

Soil water content was extensively measured in a three ha portion of a field located 10 km south of Durand, MI, to compare them with model predictions. The field was planted with soybeans on May 5, 1997. A digital elevation model (DEM) was created for the site using a high accuracy differential global positioning system (DGPS) at 1 m grid resolution (F.J Pierce and T.G.Mueller, personal communication, 1997). Using the DEM, the following topographic attributes were determined for the site: elevation, slope, plan curvature and profile curvature. A regular grid consisting of 28 grid locations spaced 30.5 m apart was imposed on the experimental area. Latitude, longitude and elevation of each grid points were determined with DGPS. Neutron probe access tubes were installed at each of the 28 grid locations. A neutron moisture gauge was used to measure the spatial variability of soil water content at 15-cm increments to the depth of the C horizon or a maximum of 150 cm depth, which ever occurred first. Measurements on soil water were taken on a weekly basis throughout the season. The upper and lower limit of soil water availability was determined using soil water measurements taken in the field, and from empirical equations based on soil texture (Ritchie *et al.*, 1999).

The spatial structure for each parameter was assessed using a semivariance analysis (data not shown). Soil water measurements taken on each grid point were interpolated using punctual kriging technique available in GS+ Version 3.1a (Gamma Design Software, 1999).

A simulation run of SALUS-TERRAE was done using a soil type with no restricting soil layer for the entire area with a high rainfall (76 mm) occurring on the first day. This simulation was chosen to demonstrate the ability of the model to partition the vertical and horizontal subsurface flow. The performance of the model was evaluated by the RMSE between the predicted and observed values.

The model results for the first simulation run are shown in Figures 1 through 8. The units used in the outputs for all the variables are in cm (height of water). Figure 1 shows the ponding capacity of soil surface. The model was able to correctly determine that the depression areas have higher surface ponding capacities. The net surface flow (Fig. 2) is calculated by subtracting the amount of water coming onto the element from the one leaving the element. The highest value (-5 cm) is observed on top of the

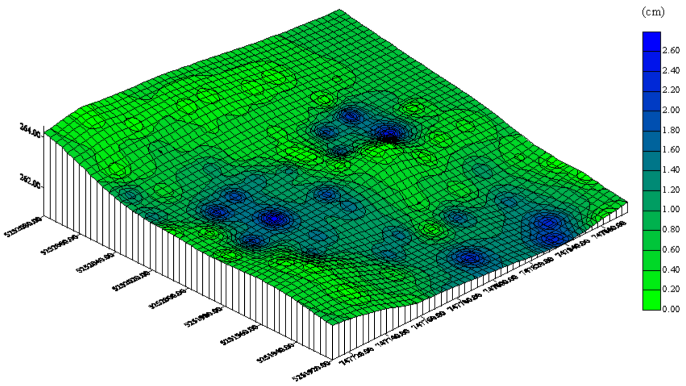

Fig. 1 - Map of surface ponding (cm)

Fig. 1 - *Mappa del ristagno idrico superficiale (cm)*

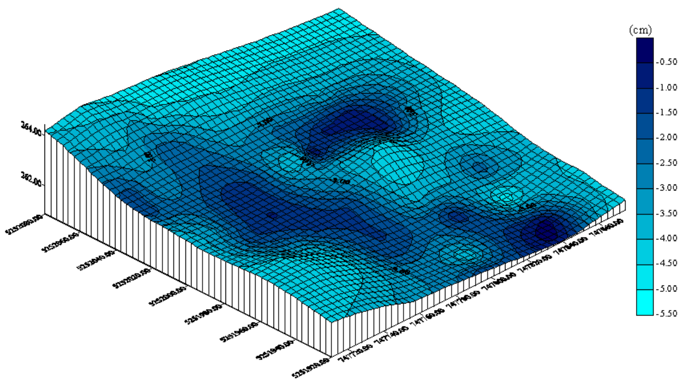

Fig. 2 - Net surface flow (cm) calculated as difference between runon-runoff

Fig. 2 – *Flusso superficiale netto calcolato come differenza tra apporto da ruscellamento e perdita da ruscellamento*

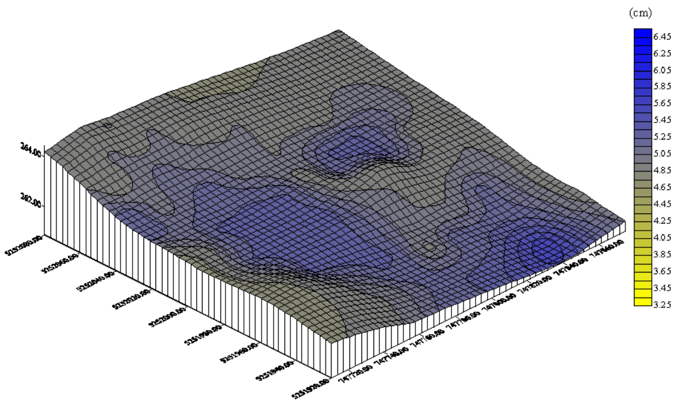

Fig. 3 - Soil water content (layer 0-26 cm)

Fig. 3 - *Contenuto idrico del terreno per lo strato 0-26 cm*

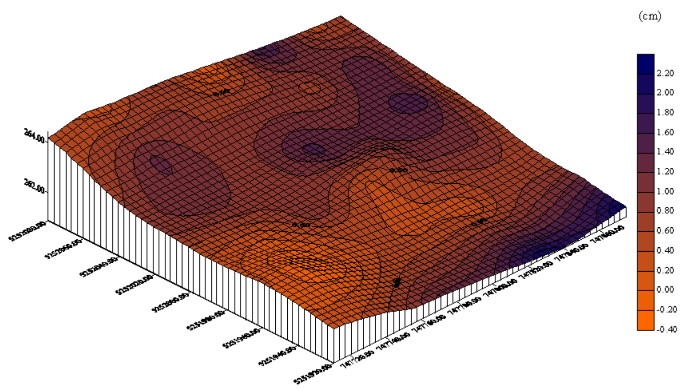

Fig. 4 - Error map of soil water content (cm) for the layer 0-26 cm

Fig. 4 – *Mappa dell'errore del contenuto idrico (cm) del terreno per lo strato 0-26 cm*

landscape since those elements do not have water running onto them, while the area with values close to zero represents areas where the soil receives as much water as it loses. Figure 3 shows the soil water content for the 0-26 cm. The soil water content for the 0-26 cm is uniform across the field, except for the low elevation areas, which are higher due to accumulation of surface flow onto the elements. The error map, calculated as difference between the soil water content measured and the soil water content simulated is shown in figure 4.

The model performance was compared using the root mean square error (RMSE). The RMSE observed was 0.51 cm, for the 0-26 cm depth and 0.62 cm for the 26-77 depth (Figure 5). The simulated soil water content for the points located in the upper saddle (263 m) are compared with soil water measurements in Figure 6. The RMSE observed for this comparison were 0.39 cm for the 0-26 cm depth and 0.52 cm for the 26-77 cm depth.Figure 7 shows the comparison between simulated and simulated soil water content for the lower saddle point (262 m). A RMSE of 0.46 cm and 0.49 was observed for this comparison for the 0-26 cm and 26-77 cm depth. An evaluation of the model performance was also done for the depression area of the streamline selected (260 m). The RMSE observed for this evaluation were 0.47 cm for the 0-26 cm and 0.59 cm for the 26-77 cm depth (Figure 8).

Conclusions

This paper reviews the principles of digital terrain analysis and the description of data source, accuracy and resolution of digital elevation models. The paper also describes the application of SALUS-TERRAE, a digital terrain model with a functional spatial soil water balance model, at a field scale to simulate the spatial soil water

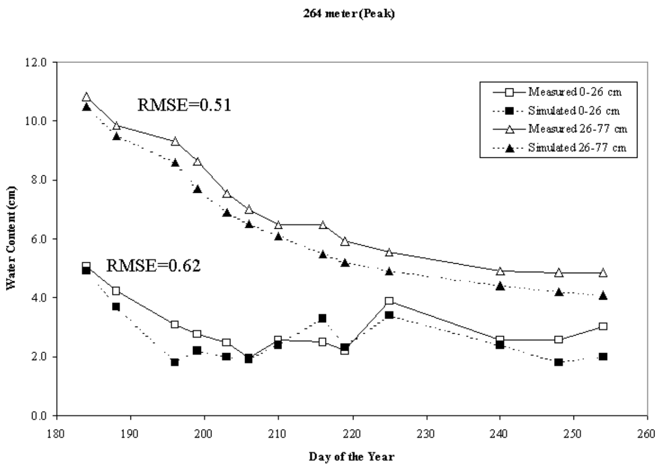

Fig. 5 - Measured and simulated water content for the soil profile (0-26 cm)and (26-77 cm) for the high elevation zone (peak) for the entire season.

Fig. 5 *– Contenuto idrico del terreno per lo strato 0-26 cm e 26-77 cm misurato e simulato per una zona di elevata altitudine (cima) per l'intera stagione.*

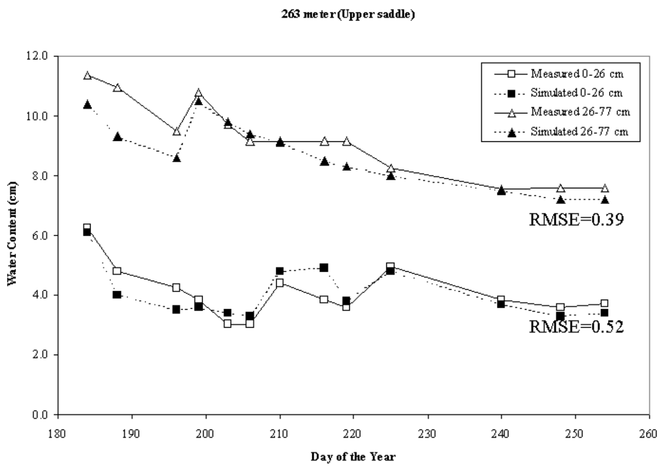

Fig. 6 - Measured and simulated water content for the soil profile (0-26 cm)and (26-77 cm) for the medium elevation zone (upper saddle) for the entire season.

Fig. 6 *– Contenuto idrico del terreno per lo strato 0-26 cm e 26-77 cm misurato e simulato per una zona di media altitudine (sella superiore) per l'intera stagione.*

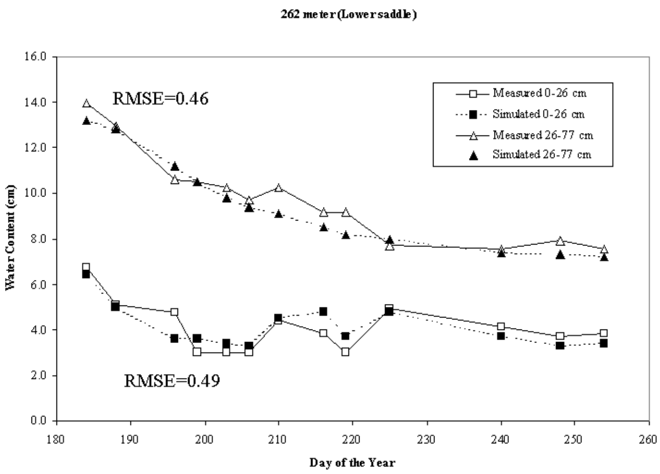

Fig. 7 - Measured and simulated water content for the soil profile (0-26 cm) and (26-77 cm) for the medium elevation zone (lower Saddle) for the entire season.

Fig. 7 *- Contenuto idrico del terreno per lo strato 0-26 cm e 26-77 cm misurato e simulato per una zona di media altitudine (sella bassa) per l'intera stagione.*

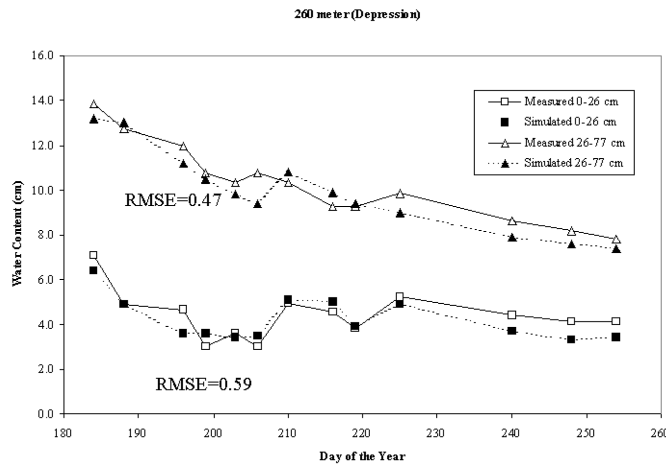

Fig. 8 - Measured and simulated water content for the soil profile (0-26 cm) and (26-77 cm) for the low elevation zone (depression) for the entire season.

Fig. 8 *– Contenuto idrico del terreno per lo strato 0-26 cm e 26-77 cm misurato e simulato per una zona di bassa altitudine (cima) per l'intera stagione.*

balance and how the terrain affects the water routing across the landscape.
The model was able to partition the subsurface lateral flow and the vertical drainage differently for the soils presents in the field. The model provided excellent results when compared to the field measured soil water content. The RMSE between measured and simulated results varied from 0.22 cm to 0.68 cm.
The performance of SALUS-TERRAE is very promising and its benefits can be quite substantial for the appropriate management of water resources as well as for identifying the areas across the landscape that are more susceptible for erosion. It is necessary to further validate the model with different soils, weather and terrain characteristics.

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