Soil & Tillage Research 112 (2011) 8–17

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Runoff estimation in small rural watersheds using DEMS in North West of Argentina

H.G. Rosatto [a,*], A. Tolon-Becerra [b], G. Botta [a], M.E. Presutti [c]

[a] University of Buenos Aires, Agronomy Faculty, Av. San Martín 4453, Buenos Aires, Argentina
[b] University of Almería, Ctra Sacramento s/n, La Cañada de San Urbano 04120, Almería, Spain
[c] National University of La Plata, Agronomy Faculty, 1900, La Plata, Argentina

A R T I C L E I N F O

Article history:
Received 16 August 2010
Received in revised form 12 October 2010
Accepted 26 October 2010
Available online 15 December 2010

Keywords:
Average slope
Level
Basis
Topographic parameters

A B S T R A C T

Basic information from analytical-descriptive methodologies on the relief of watersheds provides the necessary physical parameters for studying natural resources for, e.g., integrated management of watersheds, environmental impact, soil degradation, deforestation, conservation of water resources, and so forth. Geographic information systems can be used for all of these processes, which are linked to a strong spatial component. Digital elevation models (DEM) and their derivatives are a relevant component of these data sources. The parameters found from these models, such as the slope, are used directly or indirectly (as a component of these factors) in many surface runoff estimation equations. In Latin America, the Rational Method has been and continues to be one of the most widely used for the study of microdrainage in small watersheds. The experiment was conducted in the Yatasto district of the Province of Salta, North West Argentina and has an approximate surface of 270 hectares. This zone is located on the piedmont plain of the Metán sierra, where crops are grown, with relatively high slopes and high potential of soil erosion. In this area were studied five small rural watersheds all of them within the total DEM study area and none of them over 81 hectares. This work studied whether potential surface runoff found from the Rational Method (RAMSER) in small rural watersheds shows significant differences depending on whether the mean slopes are found from the DEM derived model or by the usual field methodology. We found that the small-sized grids increase the average slope (between 045% and 0.79%) found over those found from field data. The differences observed in volume of the peak runoff (between 0.003 $m^3 s^{-1}$ and 0.062 $m^3 s^{-1}$) were not significant. The results assure that there are no differences in the parameter evaluated (average slope) under the studied methodology and conditions.

1. Introduction and literature review

As mentioned by Marquinez (1994), the biological landscape is made up of complex, nonlinear systems. Topography exerts a strong influence on many of the variables that intervene in ecosystem dynamics. The action of water, and consequently, the many biological processes conditioned by it, is closely associated with the shape and altitude of the terrain in which they develop.

This dependence has long been recognized in edaphology, climatology, botany, zoology, ecology, and so on, which have commonly recurred to consider the altitude, the slope of the terrain or the orientation of hillsides as critical variables in understanding the body of their knowledge. As mentioned in Cheng et al. (2006), due to the complexity of this problem, many studies have been performed only to describe topographic parameters (local hill slope gradient, upslope contributing area) (Patton and Schumm, 1975; Montgomery and Dietrich, 1992; Desmet and Govers, 1997).

Until the seventies, topographical maps (contour lines) were practically the only tool for evaluating this influence. But interpretation and in fact, the usefulness of these maps, very agile for visual perception of the surface topography, is limited for quantitative analyses. Information Technology opened a new possibility, numerically describing the altitude of the terrain or any of its other characteristics.

The term digital terrain model (a synonym of digital elevation model), apparently originated in the Photogrammetry Laboratory of the Massachusetts Institute of Technology in the fifties. The pioneering work of Miller and Laflamme (1958) already established the first principles of use of digital models for treating technological, scientific and military problems (Felicísimo, 1994).

These models, as mentioned by Turner (1970), may be classified as Iconic (where the relationship with reality is through

---

[*] Corresponding author. Tel.: +54 11 45248008; fax: +54 11 45248008.
E-mail address: rosatto@agro.uba.ar (H.G. Rosatto).

0167-1987/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.still.2010.10.010

morphological properties), Analogical (where some property is represented, but not morphological replicates) and finally, Symbolic models (where the real object is represented by mathematical symbolization). Digital elevation models are symbolic and the mathematical symbolization is called a "mathematical algorithm".

Both the construction of the models derived and dynamic simulation processes are possible through numerical algorithm design, that is, constructing explicit sequences of mathematical operations that lead to the solution of concrete problems (Felicísimo, 1994).

A digital elevation model (DEM) is a representation of the terrestrial surface and as such, provides the basis for digital extraction of topographic parameters. The rest of the functions supplied by DEM are developed based on these parameters (Rosatto, 2005).

The creation of a DEM involves interpolation of an elevation surface from point elevations or from existing topographical databases. The resolution (grid size) of the created DEM and the specific interpolator (algorithm) used exert a considerable influence on the final DEM, and hence any attributes derived from it (Schoorl et al., 2000).

Many authors have proposed classifications or described DEMs based on the construction method or on the database source (Cambardella et al., 2004; Moorman et al., 2004; Reyniers et al., 2006; Taconet and Ciarletti, 2007).

Other authors have proposed methods for determining the accuracy of DEMs. In this sense, the most widely used measure (Li, 1991; United States Geological Survey, 1998; Xiaojun and Hodler, 2000), for reporting the accuracy of a DEM is a measure of dispersion, the RMSE (Root Mean Square Error). Schiewe Jochen (2000) proposes a DEM classification based on this measure (RMSE).

Classification by accuracy in determining height

Accuracy class	Standard deviation	Methods of finding data on height for generating the DEM
Very high	<0.1 m	Topography of terrain, differential GPS (DGPS),
High	0.1–1 m	Differential GPS (DGPS), aerial photogrammetry
Medium	1–5 m	Airborne interferometric radar
Low	5–20 m	Image stereoscopy, map scans, satellite interferometric radar
Very low	>20 m	

Digital elevation models have been used in many studies related to soil and tillage. Recent research on the relationship between soil redistribution and topography has been greatly aided by the ease with which terrain attributes can be derived from any digital elevation model (DEM) (Pennock, 2003).

Taconet and Ciarletti (2007) used DEMs to study classic roughness parameters such as the mean square error of height, and the correlation between length and tortuosity. They affirm that stereo photogrammetry provides DEMs that facilitate precise studies of the geometrical properties of soils that can definitely be used for hydraulic and erosion studies.

Reyniers et al. (2006) used a DEM generated by differential geoposition system to analyze topography of the field, in grain and straw yield maps. In a study done to quantify and explain the origin of morphological and geochemical properties of terraces (in the Massif Central, France), Salvador-Blanes et al. (2006), used two DEMs (2.5-m resolution) constructed in the studied area. A 10-m-resolution DEM was used by Fua et al. (2006), to estimate the impact of direct sowing in eroded soils, and the sediment yield in the Pataha Creek Watershed, a typical unirrigated agricultural watershed in southeast Washington.

The mechanical properties of soil have also been studied, and there are many rural engineering approaches to define the main constraints of force distribution related to farm machinery traffic (Botta et al., 2004, 2006a,b, 2007, 2008), but soil studies, such as the one by Horn et al. (2005), currently attempt to include in their approaches, not only the force of the mechanical properties of soil horizons, but also their interdependence with hydraulic properties. These hydraulic properties may be studied from DEMs and their derived models. The route of water on the terrestrial surface is conditioned by the shape of that surface (Wood, 1996). The hydrological characteristics, such as slope, orientation and curvature can be taken from DEMs.

Some of the characteristics mentioned (such as slope), are used in equations that estimate potential runoff. This is the case of the Rational Method (RAMSER). The results of Takken et al. (2001), suggest that the prediction of soil erosion and deposition in a plot, as well as complete soil loss in a field, can be significantly improved by combining the effects of the runoff pattern of controlled tillage with detailed topographic data. Both parameters are considered in the Rational Method.

In Latin America, the Rational Method has been and continues to be one of the most widely used. Botero Gutiérrez (2008) argues that it is the simplest approach to evaluate the flow produced by precipitation. The Rational Method, adapted by various authors, is usually used for the prediction of maximum flow rates. The Rational Method is recommended in catchment's areas of over 10 hectares and with several soil uses for estimating the amount of water that can be made use of (Salinas Acosta et al., 2010). Prieto Bolívar (2004) mentions in his book that runoff depends on such factors as regional rainfall characteristics and the type of drainage area, and recommends the use of the Rational Method adapted to the metric system. Pannone and Szogi (1984) mention the use of the Rational Method for characterization of surface runoff in two small agricultural watersheds. The Rational Method is used in small watersheds, and simulation models for larger watersheds. In this hand, Tucci and Bertoni (2003) argue that the RAMSER is used for estimation of micro-drainage, and hydrological models for calculating drainage hydrographs are used in macro-drainage. The Rational Method may be used for watersheds of up to 2 km^2 (200 hectares).

However, a DEM has to be a test bed. All the elements with representative incidence in the environment have to be synthesized in the model, but if it is very rigorous, the information storage requirements and analytical processes could be very seriously compromised. At the other extreme, an interpretation of the reality that is too superficial and relaxed could omit transcendental aspects (Morillo Barragán et al., 2002). Various authors have approached the influence of grid size on DEMs (in raster data models), and some of them mention the importance of using small grid sizes in DEMs at plot scale. Sørensen and Seibert (2007) studied different grid sizes to determine the effects of smaller-sized grids and decreased information content. Taconet and Ciarletti (2007) presented their results on the effect of DEM grid size on the precision of each roughness parameter studied.

Sørensen and Seibert (2007) also show considerable differences between topographic indexes calculated from DEMs with different grid resolutions. They found that interpolating DEMs with a higher resolution (smaller-sized grid) provided more similar topographic distributions of the humidity index (the parameter studied).

Wolock and McCabe (2000) found that increasing DEM grid size tends to cause a decrease in the average slope. Other authors have approached the use of small grid sizes in their studies (Cheng et al., 2006, 2007; Salvador-Blanes et al., 2006; Fua et al., 2006).

Outlined hypothesis were:

Table 1
Soil physical and mechanical properties.

Depth (mm)	0–200	200–400	400–600	600–800
Soil organic carbon (kg^{-1})	16.5 ± 4.6	7.00 ± 2.1	5.10 ± 1.1	4.3 ± 1.0
Total nitrogen (g kg^{-1})	1.80 ± 0.08	0.90 ± 0.02	0.70 ± 0.00	0.8 ± 0.00
C/N ratio	9.10	7.70	7.20	5.4
Clay (<2 m) g kg^{-1}	230 ± 3.37	263 ± 2.30	330 ± 2.88	372 ± 2.63
Silt (2–20 m) g kg^{-1}	308 ± 4.81	299 ± 4.01	309 ± 2.31	239 ± 1.89
Silt (20–50 m) g kg^{-1}	454 ± 4.51	433 ± 3.46	357 ± 4.01	385 ± 3.86
Fine sand (100–250 mm)	8 ± 1.38	5 ± 1.10	4 ± 0.96	4 ± 1.12
pH in H_2O (1: 2.5)	6 ± 0.02	5.6 ± 0.01	6.3 ± 0.03	6.2 ± 0.02

Table 2
Parameters of the five watersheds.

Watershed	Watershed surface (hectares) (totality cultivated)	Principal channel length (meters)	Maximum level difference (meters)	Soils	Vegetation
Number 1	78.9	2110	26	Sandy loam soils	Culture of cranberry
Number 2	23.8	1231	18	Sandy loam soils	Culture of cranberry
Number 3	7.4	876	10	Sandy loam soils	Culture of cranberry
Number 4	12.9	961	12.5	Sandy loam soils	Culture of cranberry
Number 5	10.7	800	8.5	Sandy loam soils	Culture of cranberry

(1) It is possible to determine an ideal grid size to generate DEMs with enough accuracy and size to diminish the processing requirements in later uses.
(2) The derivated model of slopes allows the use in the determination of potential superficial runoff (with the rational formula) in small rural watersheds.

2. Objectives

The main objectives of this work were to: (a) determine the grid size that shows the highest elevation accuracy and a size or “informatics’ load” that allows its use without costly storage or processing requirements and (b) evaluate, in five small rural watersheds, whether potential surface runoff calculated by the Rational Method (RAMSER), is similar or different when the average slope used is found from the slope model (a DEM derivative) or in the field.

3. Materials and methods

3.1. The site

The experiment was conducted in the Yatasto district of the Province of Salta, North West Argentina (25° 58′S, 64° 95′W) at an altitude 796 m above sea level; this zone is located on the piedmont plain of the Metán sierra, where crops are grown, with relatively high slopes and high potential of soil erosion. Soil management included, 7 years of a very usual regional crop: cranberry (*Vaccinium macrocarpon Ait.*). The cranberry crops in this zone are grown under antifreeze protection systems, with a high pluviometry for that protection, which, joined to the slopes, presents a high risk of potential runoff. The soil is and Haplustol (Soil Conservation Service, 1994), with an organic matter content ranging from 1.4% (w/w) in the surface to 0.5% at 0.6 m depth. Soil physical and mechanical properties are given in Table 1. The study area (plot scale) has an approximate area of 270 hectares (Fig. 1) and the relief may be seen on the contour lines map (Fig. 2).

In the experimental area the heaviest intensity of precipitation is 50 mm h^{-1}. This is arrived at from the maximum rainfall intensity in 24 h: 139 mm, transformed by the Hersfield factor from 123 mm.dia^{-1} × 1.13 day (*Differing intensities in 24 h, exceeding the Maximum Daily Rainfall*, may be found as recommended by Hersfield (1961), by multiplying the Maximum Daily Rainfall by 1.13), and corresponds (taking the rainfall intensity in a time period of 1 h using the Evans factor of 0.36; Evans, 1971), to a storm of approx. 50 mm h^{-1}.

3.2. Parameters in the five watersheds

Historically, research on surface runoff and soil erosion has mainly been carried out at test plot scale, in which the dominant control factor is the slope gradient. However, plot-scale runoff patterns may be very different (Takken et al., 2001). For this reason, this study was performed in test sites in five small rural watersheds (field scale), all of them within the total DEM study area and none of them over 81 hectares.

The morphometric parameters found for the five watersheds (Table 2) were determined from the contour line map (Fig. 2).

3.3. Construction of the DEMs

The basic unit of information in a DEM is altitude, *z*, along with data for *x* and *y*, expressed in a geographic projection system for precise spatial georeferencing. The determination of these data (mainly altitude) and its transfer to digital format is the first step in generating the DEM.

Fig. 1. Satellite image of the site.*Source*: Digital Globe—Google

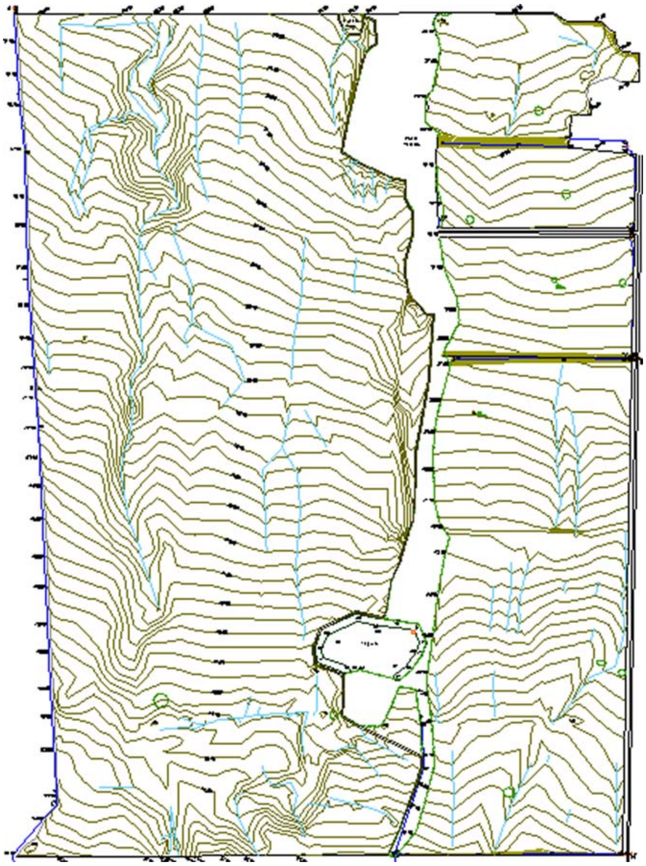


Fig. 2. Contours map of the site (equidistance 0.50 ms), used in the digitalization*Source*: Authors

In this study, to generate the DEM, an indirect methodology was used (manual scanning of contour lines) and the "DEM from Contour" algorithm (PCI Geomatica software version 9). This methodology was used because in the selected zone, the only altimetry information available are the level curves planes (analogical), that is why we chose to digitalize that planes, in order to generate the database. According to Rosatto (2005), DEMs, depending on the methodology and the interpolation algorithm on which they are based, may be classified differently. According to this, the DEM constructed is classified as "Strings". Analogical documents (contour line map, see Fig. 2) were scanned manually using the methodology proposed by Solari et al. (2007). This information was used to generate the DEMs.

3.3.1. Grid sizes

According to the studies and recommendations of different authors mentioned in the introduction and bibliographic review (Sørensen and Seibert, 2007; Taconet and Ciarletti, 2007; Wolock and McCabe, 2000; Cheng et al., 2006, 2007; Salvador-Blanes et al., 2006; Fua et al., 2006), it was decided to use three different grid-size resolutions, 2.5 m; 5.0 m and 10.0 m. Also these authors mention the importance of knowing the altimetry quality of the DEM in order to be able to evaluate their potential use. It also mention that the best altimetry quality results, are based on the data source and grid sizes used on its generations.

3.3.2. Statistical analysis

3.3.2.1. Model accuracy. A set of control points considered the "field truth" is usually used to evaluate the accuracy of elevation models. These points are compared to those generated by the model at the same planimetric position. The difference between the two heights is the error, and the statistical values used for evaluating DEM accuracy are found with these errors. The best control points are those found in the field (United States Geological Survey (USGS), 1998). These control points are statistically considered "true" with no error. As recommended in the literature (Li, 1991; USGS, 1998; Xiaojun and Hodler, 2000), the RMSE (Root Mean Square Error) was used to determine DEM accuracy.

The following formula was used for its calculation:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} (yi - yj)^2}{N}}$$

where yi is the model height (z), yj is the real height (z) and N is the number of pairs of data modeled.

To corroborate the results, the population variances (based on sample variances) were compared using G.W. Snedecor's *F*-test (Pimentel Gomez, 1978). A null hypothesis (H0) of equal variances and a hypothesis (H1) of inequality were proposed.

3.4. Potential surface runoff

There are many equations and methodologies for calculating potential surface runoff in watersheds. In this work, the Rational Method (RAMSER) was used because this methodology is widely used by many Government bodies in Argentina, and recommended in Latin America. Furthermore, as shown in the bibliographic review, it is recommended for estimating microdrainage and small rural watersheds, conditions similar to those in this study. It is important to noted that in many cases, the derivated models not always maintain the altimetry quality of the original DEM, and in order to calculate the superficial runoff with the selected methodology, the slope is one of the parameters involved.

Aciar et al. (2008) mention in their work on the Bolivian Chaco that runoff depends on rainfall (duration, intensity and distribution), microdrainage characteristics (size, shape, topography), type of soil and cover. They also suggest the Rational Method as one of the methodologies to be used. In their report for a locality in Jujuy Province (Argentina), Paoli and Franzoni (2008) mention calculating runoff in the study area using the Ramser Formula.

For rural watersheds of less than 690 hectares, Villanueva et al. (2003) among others, believe that the Rational Method (RAMSER) would be closer to agricultural problems both because of the source of the original data and the method used.

Botero Gutiérrez (2008) mentions that it is approximately sufficient in small watersheds (<101 hectares), but when applied to large watersheds, it has the drawback of overestimating flood peak magnitudes.

The RAMSER formula:

$$Q = \frac{C \cdot I \cdot A}{360}$$

where Q is the peak runoff flow rate (in $\mathrm{m^3\,s^{-1}}$), C is the dimensionless runoff coefficient, I is the corrected rainfall intensity in the watershed over runoff concentration time (Tc), in $\mathrm{mm\,h^{-1}}$, and A is the area of the watershed in hectares.

Table 3
The Root Mean Squared Error (RMSE) calculated for three grid sizes.

Grid sizes	2.5 m	5.0 m	10.0 m
Summation of the square errors	31.83	31.53	30.59
Number of samples	58	58	58
RMSE (m)	0.741	0.737	0.726

Table 4
Average slopes obtained by Alvord's method.

Watershed	Total length of watershed contour lines (m)	Equidistance (vertical interval between curves) (m)	Surface of watershed (m^2)	Average slope calculated
Number 1	34.009	0.50	787.000	2.16%
Number 2	7.262	0.50	230.000	1.58%
Number 3	2.931	0.50	74.000	1.98%
Number 4	4.296	0.50	129.000	1.67%
Number 5	3.263	0.50	107.000	1.53%

Table 5
Obtained histograms (of each watershed) from slope map derivate from the 10 m grid size DEM.

Watershed	Minimum (°)	Maximum (°)	Average (°)	Median (°)	Mode (°)	Standard deviation	No. pixels
1	0.50968	5.9891	1.559	1.3872	1.2374	0.579	7701
2	0.61532	3.6607	1.344	1.3291	1.3529	0.181	2453
3	0.51134	3.4109	1.393	1.3382	1.3382	0.427	715
4	0.56439	3.7761	1.410	1.3798	1.3673	0.321	1236
5	0.61553	2.5618	1.321	1.2922	1.2846	0.235	1356

Table 6
Average Slope obtained by Alvord's method and from the slope model derivative from the selected DEM.

Slope average Used method	Watershed number 1 Slope average (%)	Watershed number 2 Slope average (%)	Watershed number 3 Slope average (%)	Watershed number 4 Slope average (%)	Watershed number 5 Slope average (%)
Alvord's method	2.16	1.58	1.98	1.67	1.53
Slope map derivated	2.72	2.35	2.43	2.46	2.31

The parameters used in the formula (after their determination) in this study, were considered constant factors with the exception of the slope: both the one found in the field and with the derived slope model (from the selected DEM), for examining whether there are significant differences in the calculation of potential surface runoff when they are used.

3.4.1. Parameters

3.4.1.1. Average slopes. The average slope was calculated using two methodologies:

(a) The one found in the field using the Alvord method (Rosatto, 2005):

The Alvord formula:

$$\text{Average slope } (\%) = \frac{\text{Total length of coutour lines } (\text{m}) \times \text{iso distance } (\text{m})}{\text{Area watershed } (\text{m}^2)}$$

(b) The one found from the DEM based on the slope model (map), derived from the selected DEM.

3.4.1.2. Dimensionless factor (C). Calculation of "*C*" is found related to soil infiltration, plant cover, relief, rainfall intensity and soil texture. There are different methodologies for its calculation, four of which were applied and averaged: (I) Gunnedah (*Res. Stat., New S. Wales*, cited by Ibarra, 1973); (II) Dastane (cited by Puricelli, 1983); (III) Frevert (derived from the original by Ramser, 1955); (IV) Schwab et al. (1981).

3.4.1.3. Concentration time (Tc). The concentration time (*Tc*) has to be established first, before the rainfall intensity in the watersheds, *I*, can be calculated. There are also many formulas for calculating *Tc*. Some of the most commonly used were selected (those with *average slope*, the parameter studied, in the equation) and then the average of the results found was used.

The formulas used were: (I) Schwab et al. (1981), mentioned and adapted by Marelli et al. (1983); (II) Rouse; (III) Kirpich; (IV) Australian Water Commission.

4. Results and discussion

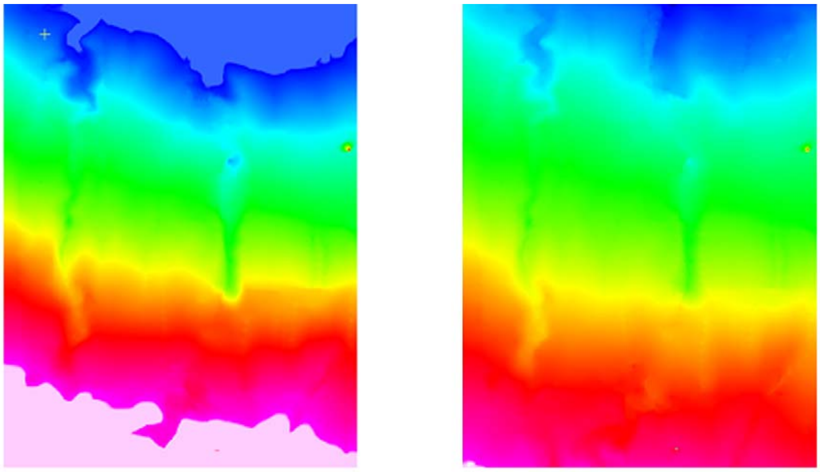
4.1. DEM construction results

In the previous section, we described the methodology used to achieve DEM, we also suggested that the choice of the grid size used for the matching step should be carefully made since it may have consequences upon the obtained DEM and on the subsequent calculation of parameter values. This part aims at quantifying these effects in order to find out the best choice for the soil in this experiment.

As said above, three grid sizes, 2.5 m, 5.0 m and 10.0 m (sizes compatible with large-scale or field models) were used to decide which grid size had the most elevation accuracy and a size or "informatics' load", which was usable without costly storage or processing requirements. The three DEMs obtained may be seen in Fig. 3.

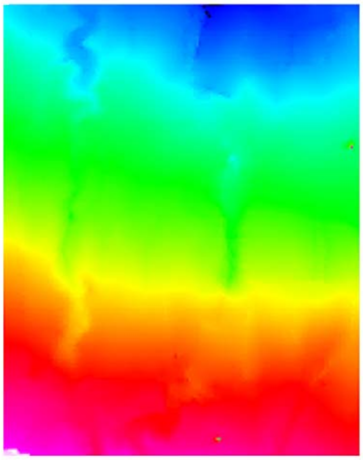
4.1.1. Statistical analysis (model accuracy)
As recommended by the United States Geological Survey (USGS) (1998), field control points were used. The number and distribution of test or control points recommended by the USGS (1998) for the DEM evaluated is a minimum of 28 points, 20 interior and 8 edge points. In this study 58 control points were used, 20 around the edges and 38 interior.

The Root Mean Squared Error (RMSE) calculated is shown in Table 3. The RMSE found for the three grid sizes studied are around 0.73–0.74 m, and the model was generated with the 10.0 m grid size, the one with the highest accuracy rate. This result is accord with Morillo Barragán et al. (2002), who indicated on the existence of a grid size which join the best possible RMSE, compatible with the minor "formatics' load" Finally, according to DEMS classifica-



DEM from Contour - Gride Size: 2.5 m

DEM from Contour - Gride Size: 5.0 m



DEM from Contour - Gride Size: 10.0 m

Fig. 3. Image of the DEMs obtained.

tions proposed by Schiewe Jochen (2000) based in the RMSE of the model, the three models obtained can be classified as high accuracy. This high accuracy obtained in small grid sizes is in accord with the ones mentioned by other authors (Cheng et al., 2006, 2007; Salvador-Blanes et al., 2006; Fua et al., 2006; Sørensen and Seibert, 2007; Taconet and Ciarletti, 2007).

G.W. Snedecor's ''*F*-test'' was used to corroborate whether the differences observed are statistically significant. ''Calculated *F*'' was the quotient between the highest and lowest standard deviation for the three models analyzed. The results show that calculated *F* (are around 1.01–1.02) is below the critical value (1.85($^{58/58}y_{0.01}$)) in the entire sample variances analyzed, demonstrating that processing is equivalent for the grid size and algorithm used. With the results and conclusions developed to this point, for the study methodology and conditions, the first goal set has been met, and the DEM based on the 10-m grid size was selected (Fig. 4) as the best for evaluating whether potential surface runoff calculated is different or similar depending on whether the mean slope is found from the slope model (derived from the DEM) or the mean slope found in the field, in the five small rural watersheds studied. The applicability of the 10 m grid is also supported by the catchment statistics examined in this study over the range of grid scales.

Consequently, as found by Zhang and Montgomery (1994), a grid scale of 10 m captures sufficient hill-slope detail for the terrain examined. The results also show that choice of digital elevation model grid size is important in determining all the geomorphic measures examined in this study, except for the hypsometric curve. A grid size should be selected which is considerably less than that of the average hill-slope length.

Table 7
Concentration time calculated.

Used equations for *Tc* calculation	Watershed number 1		Watershed number 2		Watershed number 3		Watershed number 4		Watershed number 5	
	Field slope	DEM slope	Field slope	DEM slope	Field slope	DEM slope	Field slope	DEM slope	Field slope	DEM slope
Schwab	31.7	30.0	23.5	20.3	16.1	15.4	19.0	16.6	16.8	13.6
Rouse	42.6	53.6	19.3	28.6	20.4	25.1	17.6	25.9	15.1	22.8
Kirpich	31.8	29.1	23.7	20.3	16.7	15.4	19.1	16.5	17.2	14.7
Australian water committee	34.6	33.1	30.8	28.5	26.3	25.2	28.1	26.0	26.9	24.7
Tc average (in min)	35.2	36.4	24.3	24.4	19.9	20.3	20.9	21.2	19.0	18.9

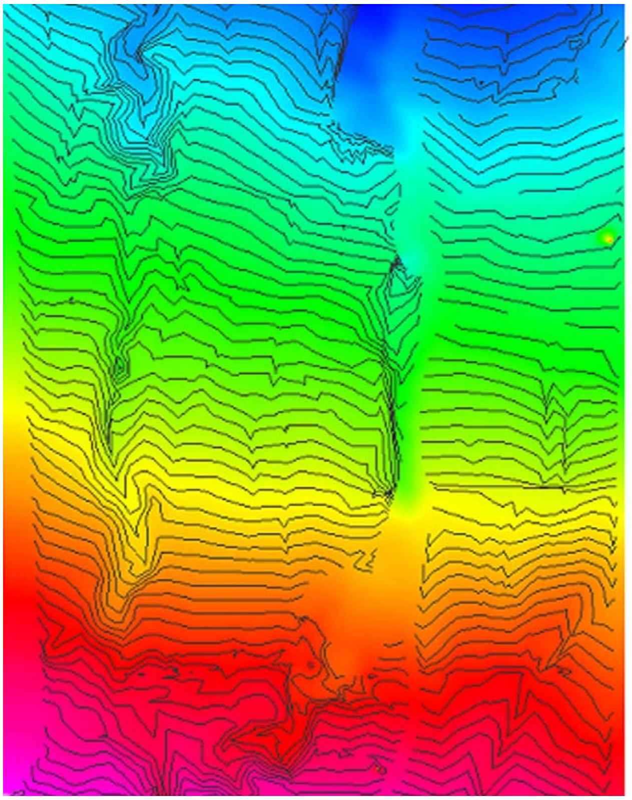


Fig. 4. DEM from contour–grid size selected: 10.0 m.

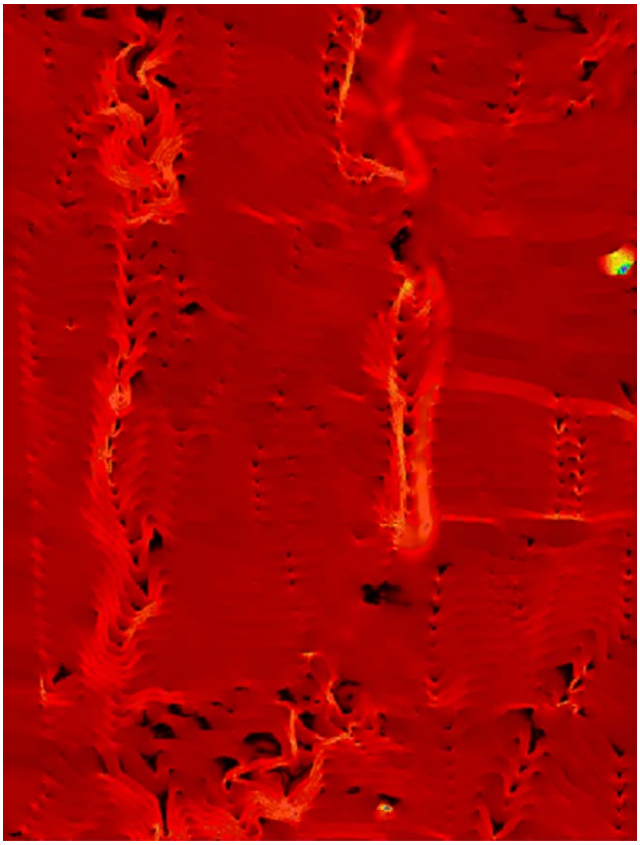


Fig. 6. Slope map model derivative from the 10 m grid size DEM.*Source*: Own

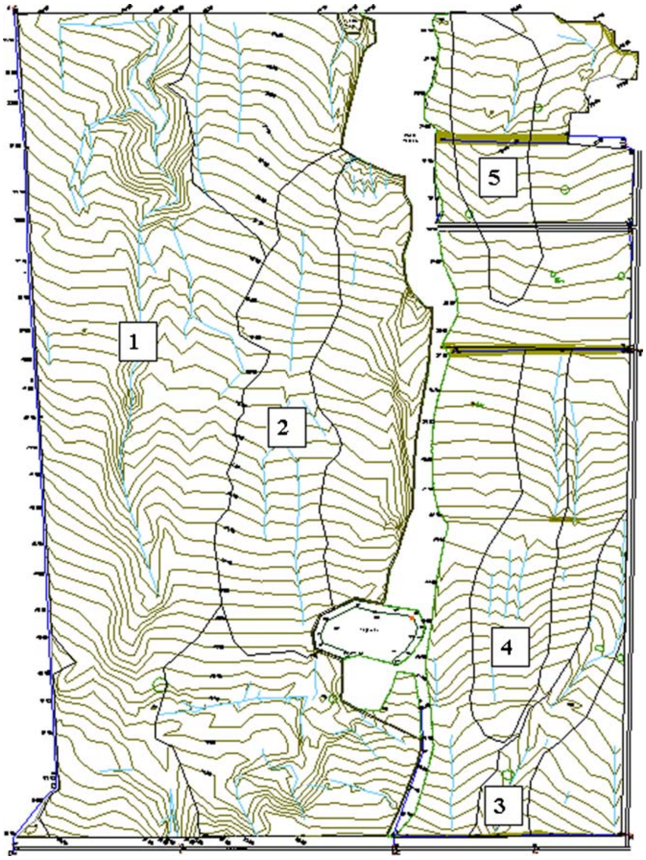


Fig. 5. Five small rural watersheds selected.

Therefore, if sufficient hill-slope detail is captured at a resolution of 10 m by 10 m for reliable geomorphological and hydrological assessment to be made, there may be no need for finer grid resolution with its accompanying fourfold increase in number of grid points with each halving in grid size (and resultant data storage and handling issues).

For the second goal, the mean slope (in addition to other parameters) of each area was calculated for each of the five small rural watersheds studied (see Fig. 5).

(a) The results with field data, using the Alvord method may be seen in Table 4.

(b) Using the slope model derived from the DEM selected (Fig. 6), the results are as observed in Table 5 and Fig. 7. *Note*: On the slope model map, each watershed was "cut out" along the water divide before finding the average slope. The average slopes found by both methods (mentioned in points a and b) are summarized in Table 6. Coinciding with the results mentioned by Wolock and McCabe (2000), we found that the small-sized grids increase the average slope found over those found from field data.

4.1.2. Dimensionless factor (C)

There is a wide range of values for each land use, slope, the ratio of vegetative cover, soil type, watershed type, and surface condition. The coefficient, *C*, is a dimensionless ratio intended to indicate the amount of runoff generated by a watershed given an average intensity of precipitation for a storm. While it is implied by the RAMSER method, that intensity of runoff is proportional to intensity of rainfall, calibration of the runoff coefficient has almost always depended on comparing the total depth of runoff with the total depth of precipitation.

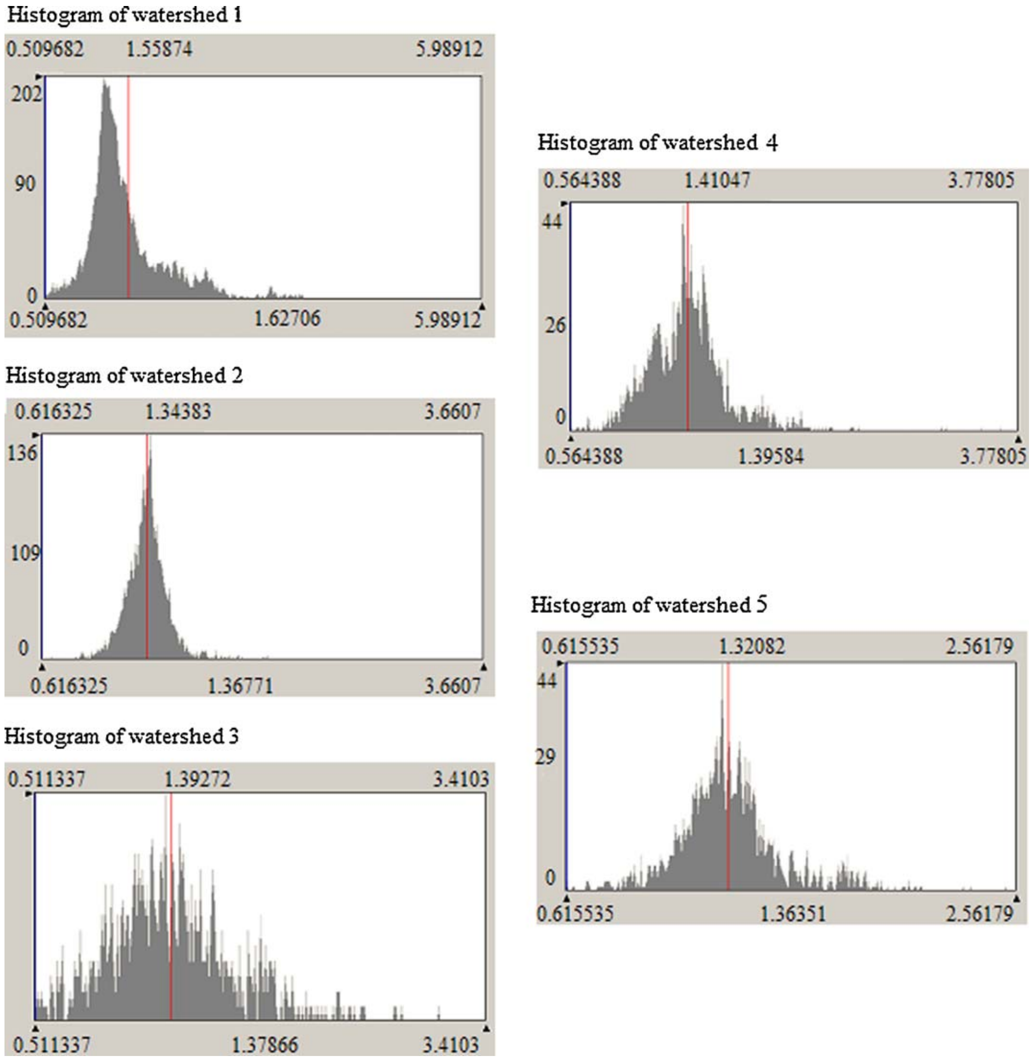


Fig. 7. Histogram screen image from slope map derivate (trimmed by water divide line) numbered and ordered from 1 to 5.

In this work, the average found: $C = 0.47$, is the same for all the watersheds, because the soil, infiltration, plant cover, relief, rainfall intensity and soil texture are similar in all five rural watersheds. This value is corresponding with permeable soils, flat slopes and dense vegetation.

4.1.3. Concentration time (*Tc*)

The concentration time found (*Tc*) for the four equations selected are shown in Table 6. The rainfall intensity (*I*) was determined with the average concentration time calculated for each watershed (Table 7) for the parameters used (slope found in the field and slope found from the model). In agreement with Botero Gutiérrez (2008), the use of a time concentration average (obtained from different mathematic models), it is an appropriate parameter for these calculations.

Different mathematic models were also used for this: (I) the one proposed by the FAO (Hudson, 1997); (II) the one proposed by Sciortino (1991), with local data from Salta (10-year recurrence); and (III) the one proposed by Schwab et al. (1981) to correct the intensity in the Kirpich method. The results may be seen in Table 8.

4.2. Calculation of Q ($m^3\,s^{-1}$) by the Rational Method for determining the potential surface runoff

With the data found, the potential runoff was calculated for each of the watersheds, for the two situations (field data and data derived from the DEM) of the parameter evaluated (average slope). In spite of the fact that the average slopes obtained from the derivated model are slightly superior to the ones obtained with field data (according with Wolock and McCabe, 2000), these

Table 8
Corrected intensity of rain calculated.

Used equations for *Tc* calculation	Watershed number 1		Watershed number 2		Watershed number 3		Watershed number 4		Watershed number 5	
	Field slope	DEM slope	Field slope	DEM slope	Field slope	DEM slope	Field slope	DEM slope	Field slope	dem slope
FAO (Hudson, 1997)	65.0	66.0	77.0	76.7	82.5	82.0	81.0	80.5	84.0	84.3
Sciortino (1991)	71.5	70.0	80.0	79.6	85.0	84.5	83.9	83.5	86.0	86.5
Schwab et al. (1981)	71.6	70.5	87.6	88.5	99.5	98.3	96.9	96.2	102.0	102.3
Intensity average (in mm)	69.4	68.8	81.5	81.6	89.0	88.3	87.3	86.7	90.7	91.0

Table 9
Potential peak runoff calculated.

Used equations for *Tc* calculation	Watershed number 1		Watershed number 2		Watershed number 3		Watershed number 4		Watershed number 5	
	Field slope	DEM slope	Field slope	DEM slope	Field slope	DEM slope	Field slope	DEM slope	Field slope	DEM slope
C	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
I (mm)	69.4	68.8	81.5	81.6	89.0	88.3	87.3	86.7	90.7	91.0
A (hectares)	78.7	78.7	23.0	23.0	7.4	7.4	12.9	12.9	10,7	10.7
Volume of the peak runoff ($m^3 s^{-1}$)	7.131	7.069	2.447	2.450	0.860	0.853	1.470	1.460	1.267	1.271
Observed differences ($m^3 s^{-1}$)	0.062		0.003		0.007		0.010		0.004	

differences did not result statistically significant for the calculation of the superficial potential runoff of the studied watersheds. Hence, the data support both hypotheses.

The maximum surface runoff flow rates are summarized in Table 9. In the statistical analysis "r^2" = 0.98 (high correlation between the model and field data) and the comparison of means by the Duncan test (*p*: 0.01), does not show significant differences between them.

5. Conclusions

(a) The equidistance (vertical interval between the successive contour lines) on the contour line map used and the scanning method used to generate the database necessary to generate the DEMs, enabled models with high elevation accuracy to be found, in fact, with an accuracy even higher than mentioned in the bibliography for the DEM generation method used (Strings).

(b) Assessing the first objective: the 10-m grid size enabled a DEM to be found that combines high elevation accuracy and a suitable size or "computational weight". We consider as a suitable size or computational weight for the DEMs, the one with joint the best accuracy (less RMSE) and less processing needs (RAM memory).

(c) For the method used (RAMSER) and the parameter analyzed (mean slope found from the model derived from the DEM), the results obtained for the five watersheds allow us to state that, for the study methodology and conditions, there are no significant differences in the peak runoff flow volumes found for the small rural watersheds whether the mean slope is found in the field or taken from the model (slope) derived from the selected DEM., assessing with this the second objective.

References

Aciar, L.M., Arzelán, M.D., Matta, D.A., Tonda, D.P., Tanco, M.P., Pastrana, D.V., Andreani, D.J.Y., Portal, M.L., 2008. Tecnologías de Manejo de Agua para Uso Humano y Animal sobre la base de Manejo de Cuencas y Cosecha de Agua en el Chaco Boliviano. Actas del XXI Congreso Argentino de la ciencia del Suelo, Potrero de los Funes (SL), Argentina.

Botero Gutiérrez, A., 2008. Análisis Espacio Temporal de la lluvia en la Cuenca Urbana de la Quebrada San Luis, Manizales–Caldas. Universidad Nacional de Colombia Facultad de Ingeniería y Arquitectura, Trabajo de Grado, Hidrología Urbana. Manizales, Colombia Disponible en: www.manizales.unal.edu.co/

Botta, G.F., Jorajuria, D., Balbuena, R., Rosatto, H.G., 2004. Mechanical behavior of an agricultural soil under different traffic intensities: effect on soybean (Glycine max l.) yields. Soil & Tillage Research 78, 53–58.

Botta, G.F., Jorajuria, D., Rosatto, H.G., Ferrero, C., 2006a. Light tractor traffic frequency on soil compaction in the Rolling Pampa region of Argentina. Soil & Tillage Research 86, 9–14.

Botta, G.F., Jorajuria, D., Balbuena, R., Ressia, M., Ferrero, C., Rosatto, H.G., Tourn, M., 2006b. Deep tillage and traffic effects on subsoil compaction and sunflower (Helianthus annus L.) yields. Soil & Tillage Research 91, 164–172.

Botta, G.F., Pozzolo, O., Bomben, M., Rosatto, H.G., Rivero, D., Ressia, M., Tourn, M., Soza, E., Vazquez, J., 2007. Traffic alternatives for harvesting soybean (Glycine max L.): effect on yields and soil under a direct sowing system. Soil & Tillage Research 96, 145–154.

Botta, G.F., Rivero, D., Tourn, M., Bellora Melcon, F., Pozzolo, O., Nardon, G., Balbuena, R., Tolon Becerra, A., Rosatto, H.G., Stadler, S., 2008. Soil compaction produced by tractor with radial and cross-ply tyres in two tillage regimes. Soil & Tillage Research 101, 44–51.

Cambardella, C.A., Moorman, T.B., Andrews, S.S., Karlen, D.L., 2004. Watershed-scale assessment of soil quality in the loess hills of southwest Iowa. Soil & Tillage Research 78, 237–247.

Cheng, H., Wu, Y., Zou, X., Si, H., Zhao, Y., Liu, D., Yue, X., 2006. Study of ephemeral gully erosion in a small upland catchment on the Inner-Mongolian Plateau. Soil & Tillage Research 90, 184–193.

Cheng, H., Zoua, X., Wua, Y., Zhanga, Ch., Zhenga, O., Jiang, Z., 2007. Morphology parameters of ephemeral gully in characteristics hillslopes on the Loess Plateau of China. Soil & Tillage Research 94, 4–14.

Desmet, P.J.J., Govers, G., 1997. Two-dimensional modelling of the within-field variation in rill and gully geometry and location related to topography. Catena 29, 283–306.

Evans, T.E., 1971. Establishment of a Programme for the Conservation of Soils, (Argentina). Consultant's report in hydrology. Pt. 1: (Main report). Pt. 2: Appendices (English). UNDP.FAO/INTA-Proyecto Argentina 26, 122 p.

Felicísimo, A.M., 1994. Parametric statistical method for error detection in digital elevation models. ISPRS Journal of Photogrammetry and Remote Sensing 49 (4), 29–33.

Frevert, R.K., 1955. Soil and Water Conservation Engineering. Wiley, New York, 479 p.

Fua, G., Chen, S., McCool, D.K., 2006. Modeling the impacts of no-till practice on soil erosion and sediment yield with RUSLE, SEDD, and ArcView GIS. Soil & Tillage Research 85, 38–49.

Hersfield, D.M., 1961. Rainfall Frequency Atlas of the United States. U.S. Department of Commerce, Weather Bureau Technical Paper 40, Washington, DC, 115 p.

Horn, R., Fleige, H., Richter, F.H., Czyz, E.A., Dexter, A., Diaz-Pereira, E., Dumitru, E., Enarche, R., Mayol, F., Rajkai, K., de la Rosa, D., Simota, C., 2005. SIDASS project. 5. Prediction of mechanical strength of arable soils and its effects on physical properties at various map scales. Soil & Tillage Research 82, 47–56.

Hudson, N.R., 1997. Soil Erosion Measured and Watersheds. Soil FAO Bulletin No. 68. Silsoe Associates Ampthill, Bedford Reino Unido, 139 p.

Ibarra, R., 1973. Diseño de las Estructuras para la Conservación de Suelos en Tierras de Cultivo. FAO, Roma.

Li, Z., 1991. Effects of check points on the reliability of DTM accuracy estimates obtained from experimental tests. Photogrammetric Engineering & Remote Sensing 47 (10), 1333–1340.

Marelli, H.J., Weir, E., Lattanzi, A.R., Díaz, R., 1983. Técnicas de Conservación de Suelos. Serie Suelos y Agroclimatología No. 3. INTA - Marcos Juárez Córdoba, 119 p.

Marquinez, J., 1994. Presentación. Libro Modelos Digitales del Terreno. Introducción y Aplicaciones a las Ciencias Ambientales. autor Felicísimo, A.M, España http://www.etsimo.uniovi.es/~feli/pdf/libromdt.pdf, 118 p.

Miller, C.L., Laflamme, R.A., 1958. The digital terrain model-theory and application. Photogrammetric Engineering 24 (3), 433–442.

Montgomery, D.R., Dietrich, W.E., 1992. Channels initiation and the problem of landscape scale. Science 255, 826–830.

Moorman, T.B., Cambardella, C.A., James, D.E., Karlen, D.L., Kramer, L.A., 2004. Quantification of tillage and landscape effects on soil carbon in small Iowa watersheds. Soil & Tillage Research 78, 225–236.

Morillo Barragán, J., Pozo Baselga, J., Pérez Preciado, F., Rodríguez Gordillo, M.C., Rebollo Castillo, F.J., 2002. Análisis de calidad de un modelo digital de elevaciones generado con distintas técnicas de interpolación. Santander, España, Proceedings of XIV Congreso Internacional de Ingeniería Gráfica http://departamentos.unican.es/digteg/ingegraf/cd/ponencias/11.pdf, 12 p.

Pannone, J.C., Szogi, A., 1984. Caracterización e Instrumentación de dos Cuencas en el Uruguay. Publicado en: Memorias del Primer Taller Nacional de Investigación sobre Cuencas Experimentales (Pág. 521 a 540). Organizado: Ministerio de Agricultura y Pesca del Uruguay. Instituto Nacional de Colonización de Colorado State University e Instituto Interamericano de Cooperación para la Agricultura, Montevideo, Uruguay, 540 pp.

Paoli, H.P., Franzoni, A., 2008. Caracterización del Escurrimiento Pluvial en la zona Productiva y Urbana Puesto Viejo (Provincia de Jujuy). Informe del Laboratorio de Teledetección y SIG–de la Estación Experimental Agropecuaria de Salta, del

Instituto Nacional de Investigación Agrícola (INTA), Salta, Argentina Disponible en http://www.inta.gov.ar/prorenoa/, 17 p.

Patton, P.C., Schumm, S.A., 1975. Gully erosion, Northwest Colorado: a threshold phenomenon. Geology 3, 83–90.

Pennock, D.J., 2003. Terrain attributes, landform segmentation, and soil redistribution. Soil & Tillage Research 69, 15–26.

Pimentel Gomez, F., 1978. Curso de estadística experimental. Primera Ed., Editorial, Hemisferio Sur, Buenos Aires, Argentina, 200 p.

Prieto Bolívar, C.J., 2004. El agua. Sus formas, efectos, abastecimientos, usos, daños, control y Conservación. Editorial Ecoe Ediciones, Bogotá, Colombia, ISBN:958-64-8356-8-2da. Ed. 380 Pp.

Puricelli, C.A., 1983. Evaluación de la Escorrentía para Cuencas reducidas. Secretaría de Agricultura y Ganadería de la Nación (Argentina): Boletín de Recursos Naturales Renovables Año 2. 3, 9–35.

Reyniers, M., Maertens, K., Vrindts, E., De Baerdemaeker, J., 2006. Yield variability related to landscape properties of a loamy soil in central Belgium. Soil & Tillage Research 88, 262–273.

Rosatto, H., 2005. Evaluación altimétrica de algoritmos generadores de modelos digitales de elevación (DEMs) en cuencas hídricas de llanura a escala predial. Proyecto del Programa de Magíster Scientiae en Manejo de Cuencas Hidrográficas - Ciclo de Tesis Final. Universidad Nacional de La Plata, Buenos Aires, Argentina, 23 p.

Salinas Acosta, A., Rodríguez Quirós, R., Morales Hidalgo, D., 2010. Manual de especificaciones técnicas básicas para la elaboración de estructuras de captación de agua de lluvia (SCALL) en el sector agropecuario de Costa Rica y recomendaciones para su utilización. Centro Mesoamericano de Desarrollo Sostenible del Trópico Seco. Universidad Nacional de Costa Rica, Chorotega - Nicoya, Costa Rica Disponible en www.cemede.una.ac.cr.

Salvador-Blanes, S., Cornu, S., Couturier, A., King, D., Macaire, J.J., 2006. Morphological and geochemical properties of soil accumulated in hedge-induced terraces in the Massif Central, France. Soil & Tillage Research 85, 62–77.

Schiewe J., 2000. Improving the integration of digital surface models. International Archives of Photogrammetry and Remote Sensing. Vol. XXXIII, Part B3. Amsterdam, 814 p.

Schoorl, J.M., Sonneveld, M.P.W., Veldkamp, A., 2000. Three-dimensional landscape process modeling: the effect of DEM resolution. Earth Surface Processes and Landforms 25, 1025–1034.

Schwab, G.O., Frevert, R.K., Edminster, T.W., Barnes, K.K., 1981. Soil and Water Conservation Engineering, Third Edition. John Wiley & Sons, Inc., New York, USA, 525 p.

Sciortino, J.B., 1991. Elementos de Hidrología de Superficie: Análisis de Hidrogramas. Apuntes Cátedra de Hidrología e Hidráulica Agrícola - Facultad de Ingeniería. UNSa, Salta.

Soil Conservation Service, 1994. Keys to soil taxonomy. In: Soil Survey Staff, 6th edition. USDA, Washington DC, USA.

Solari, F.A., Rosatto, H.G., Álvarez, A.L., Lapido, M., Barbosa, O., 2007. Comparación de dos métodos de Digitalización y su influencia en la precisión obtenida en la determinación de Parámetros Topográficos. International Review of Geographical Information Science and Technology – GEOFOCUS (Revista Electrónica) – Año 2007, no. 7. Pages 14–23 - ISSN:1578-5157. In: http://geofocus.rediris.es/principal.html. España.

Sørensen, R., Seibert, J., 2007. Effects of DEM resolution on the calculation of topographical indices: TWI and its components. Journal of Hydrology 347, 79–89.

Taconet, O., Ciarletti, V., 2007. Estimating soil roughness indices on a ridge-and-furrow surface using stereo photogrammetry. Soil & Tillage Research 93, 64–76.

Takken, I., Govers, G., Jetten, V., Nachtergaele, J., Steegen, A., Poesen, J., 2001. Effects of tillage on runoff and erosion patterns. Soil & Tillage Research 61, 55–60.

Tucci, E.M., Bertoni, J.C., Organizadores, 2003. Inundações Urbanas na América do Sul. Associação Brasileira de Recursos Hídricos, Porto Alegre, Brasil. ISBN: 85-88686-07-4. Libro financiado por: Programa Associado de Gerenciamento de Cheias desenvolvido pela Organização Meteorológica Mundial e Global Water Partnership.

Turner, J.C., 1970. Modern mathematical applied. Probability, statistic and operative investigation. Ed. Alianza, Madrid, 550 p.

United States Geological Survey (USGS), 1998. Standards for Digital Elevation Models. National Mapping Program-EEUU. , 410 p.

Villanueva, G.H., Osinaga, R.G., Chávez, A.P., 2003. El uso sustentable de los suelos (tecnología de suelos agrícolas). , U.N.Sa. Salta, Manual editado en CD-Rom. 343 p.

Wolock, D., Mc Cabe, G., 2000. Differences in topographic characteristics computed from 100 and 1000 m resolution digital elevation models. Hydrological Processes 14, 987–1002.

Wood, J., 1996. The geomorphological characterization of digital elevation models. Ph.D. Dissertation, University of Leicester, Leicester, UK, 185 p.

Xiaojun, Y., Hodler, T., 2000. Visual and statistical comparisons of surface modeling techniques for point-based environmental date. Cartography and Geographic Information Science 27 (2), 165–175.

Zhang, W., Montgomery, R., 1994. Digital elevation model, grid size, landscape representation and hydrologic simulations. Water Resources Research 30 (4), 1019–1028.