Digital Terrain Analysis and Simulation Modeling to Assess Spatial Variability of Soil Water Balance

B. Basso
Dipartimento di Produzione Vegetale
Universita' degli Studi della Basilicata
ITALY

J.T. Ritchie
Department of Crop and Soil Sciences
MICHIGAN STATE UNIVERSITY

J.C. Gallant
Division of Land and Water
Canberra, Australia
CSIRO

Abstract

The assessment of soil water spatial patterns is crucial for understanding hydrology and crop yield variability in agricultural fields. We describe a newly developed spatial soil water balance model, SALUS-TERRAE, consisting of a functional soil water balance model and a terrain analysis system (TERRAE). The model predicts a two-dimensional soil water balance where the lateral surface and subsurface flow of water is routed across the landscape using the irregular element network created by TERRAE. 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. SALUS-TERRAE was applied on an agricultural field with rolling terrain where soil water content was extensively measured. The model performed well when compared to the field measured soil water content for the entire growing season.

Rationale and Background

Due to the complexity of weather, spatial pattern of topography, soil and vegetation, soil water within a field is highly variable in space and time as result of several processes occurring at various ranges of scales.

Spatial variation in soil water is often the cause of crop yield spatial variability due to its influence on the uniformity of the plant stand at emergence and for in-season water stress.

The prediction of the spatial variability of soil water is important for various applications in the agricultural and hydrological sciences (i.e. erosion modeling, chemicals leaching to groundwater, flood warming, precision agriculture etc.). The approaches used till now to assess spatial patterns of soil moisture have basically been: (i) field measurements (ii) measurements using microwave remote sensing from a variety of platforms; (iii) wetness indices and (iv) hydrological modeling. Each group presents advantages and limitations.

The limitations of these methods provided the idea of creating a digital terrain model DTM that would include the topographic effect on the soil water balance and would be coupled with a functional soil water balance to spatially simulate the soil water balance became clear from the. This lead to the development of SALUS_TERRAE, a DTM for predicting the spatial and temporal variability of soil water balance.

Model Simulation

This study evaluates the capability of SALUS-TERRAE applied at field scale with rolling terrain where the soil water content was extensively measured.

The first simulation run of TERRAE-SALUS was done using a single, uniform soil type with no restricting soil layer (KSAT= 5 cm hr-1) for the entire area with a rainfall of 35 mm occurring on the first day. This simulation done was chosen to demonstrate the ability of the model to partition the vertical and horizontal subsurface flow.

A simulation run of SALUS-TERRAE was also done to perform a model validation at field scale. The model was set up using three different soil types. The soil types were a shallow sandy soil for the high elevation zones and peaks; a medium sandy-loam for the medium elevation zones and saddles areas; and a loamy soil for the low elevation areas and depressions. The model performance was evaluated using the Root Mean Square Error (RMSE)

Model Description

SALUS-TERRAE [*Basso, 2000*] was created combining the Ritchie vertical-soil-water balance model [*Ritchie, 1998*] with TERRAE, a digital terrain model developed by *Gallant [1999*]. SALUS-TERRAE is spatial soil water balance model composed by a vertical and newly developed lateral components of the water balance. The model requires a DEM for partitioning the landscape into a series of interconnected irregular elements, weather and soil information for the soil water balance simulation. SALUS-TERRAE is designed to predict spatial and temporal variability of evaporation, infiltration, water distribution, drainage, surface and subsurface runoff for the soil profile using a bucket approach on a daily basis for each element of the network. TERRAE is a new method for creating element networks where landscape depressions are included. 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 proportion of flow is determined by the relative lengths of contour between the two elements.

The element network created by executing TERRAE is used by the spatial soil water balance model, TERRAE-SALUS. Surface runoff is routed from one element to the next starting from the top element and moving downward.
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 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 subsurface lateral flow is computed using the following equation:

$$SLF = Kef\ (dH/dx) * (Aup/Adw)$$

where SFL is the subsurface lateral flow (cm day^{-1}), Kef is the saturated hydraulic conductivity calculated as harmonic mean between Ksat of the upslope element and the downslope element (cm day^{-1}),*dH* is the distance between the saturated layer and the soil surface *dx* is the distance between the center of the upslope element and the downslope element, Aup is the area of the upslope element (m^2) and Adw is the area of the downslope element (m^2). The hydraulic head (*dH*) is calculated by the soil water balance model, while *dx* is calculated by TERRAE.

Results

The model was able to correctly determine that the depression areas have higher surface ponding capacities (Fig. 1). The model predicted that water not infiltrated on the element located on top of the landscape runs off to the next element downslope as runon (Fig 2,3). This explains the balance observed between flow out and flow in. Both maps clearly show the effect of the landscape in the surface water routing. The highest amount of water leaving each element is 12 cm and it is observed in the depression areas due to the contributions from the upper-slope elements. The net surface flow (Fig. 4) is calculated by subtracting the amount of water coming into the element from the one leaving the element. The subsurface lateral flow is shown in figure 5. The highest amount of horizontal flow is observed in the depressions due to high soil water content present at these locations. The vertical drainage is depicted in figure 6. The drainage amount predicted is quite small throughout the landscape. This may be due to the rapid occurrence of saturation in each soil layer that determined higher subsurface later flow.
Figure7 (a through d) shows the measured and simulated results for the soil water content for 0-26 and 26-77 cm soil depth for the entire season using four points along a streamline (from the top-peak, to the bottom of landscape-depression). The model performance was compared using the root mean square error (RMSE).

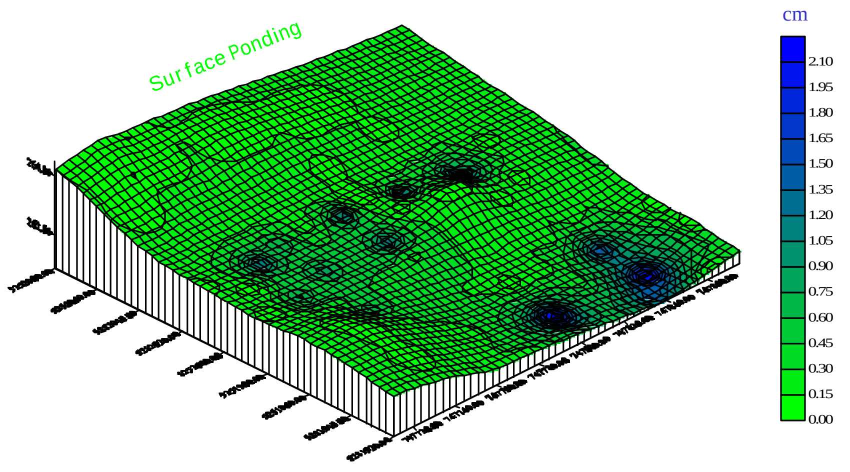
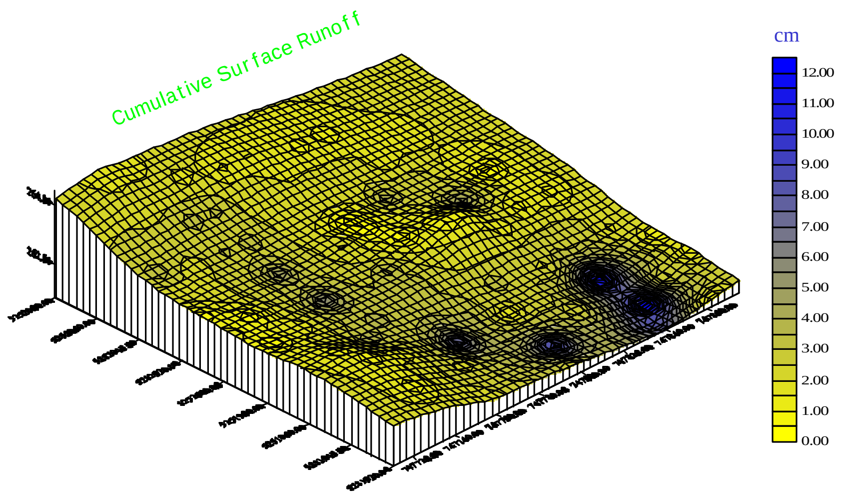


Fig. 1

Fig. 2



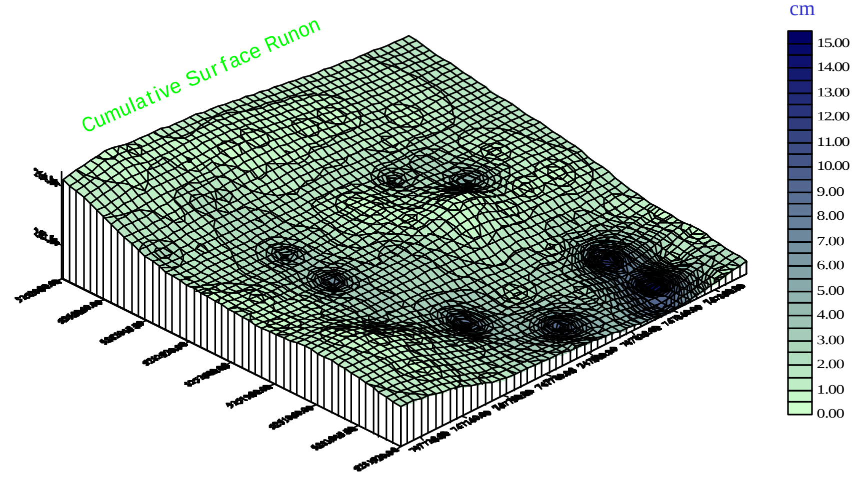
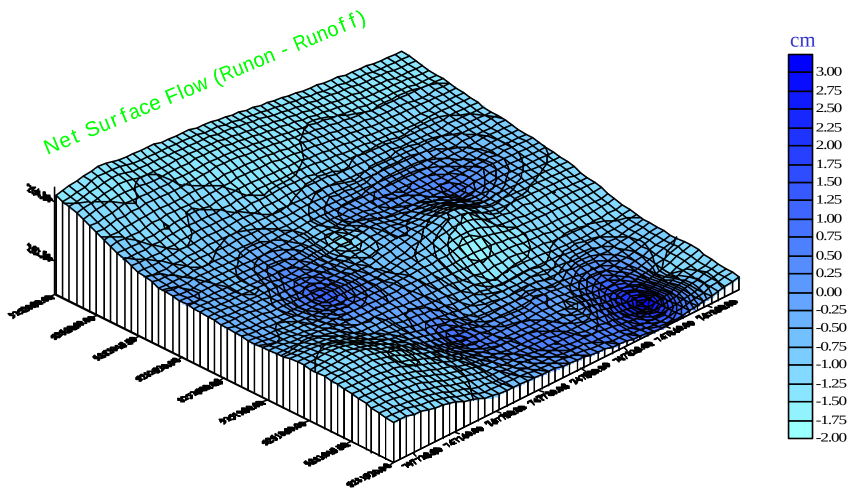


Fig. 3

Fig. 4



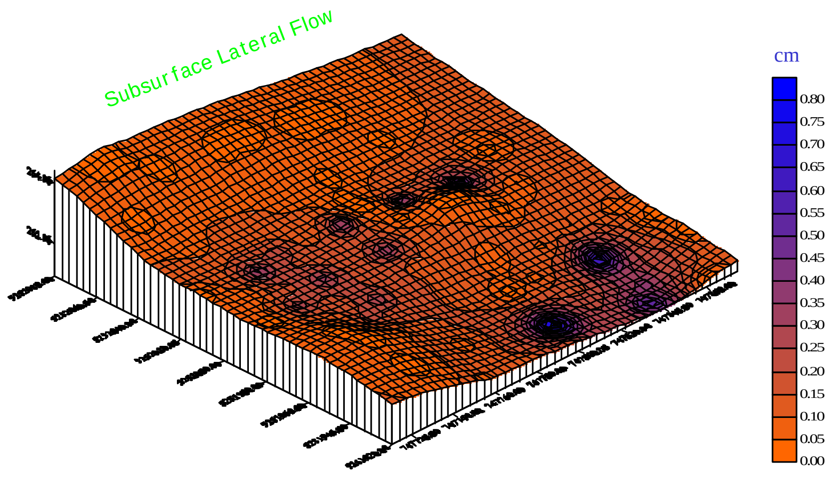
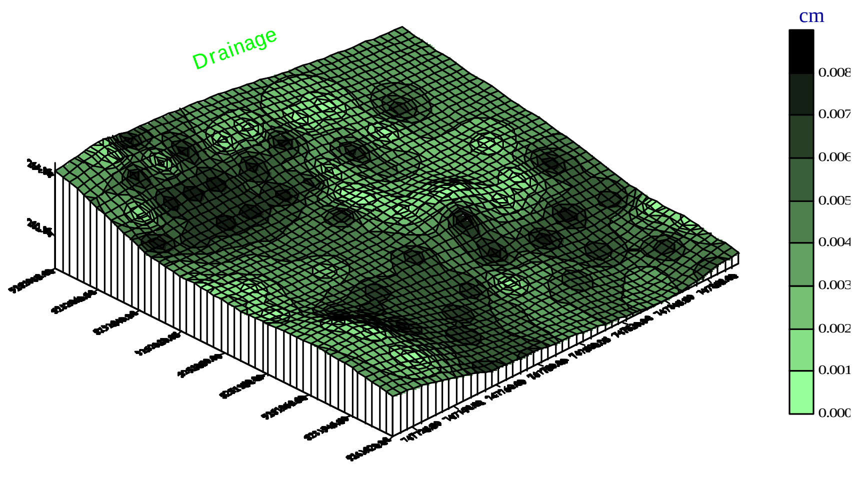


Fig. 5

Fig. 6



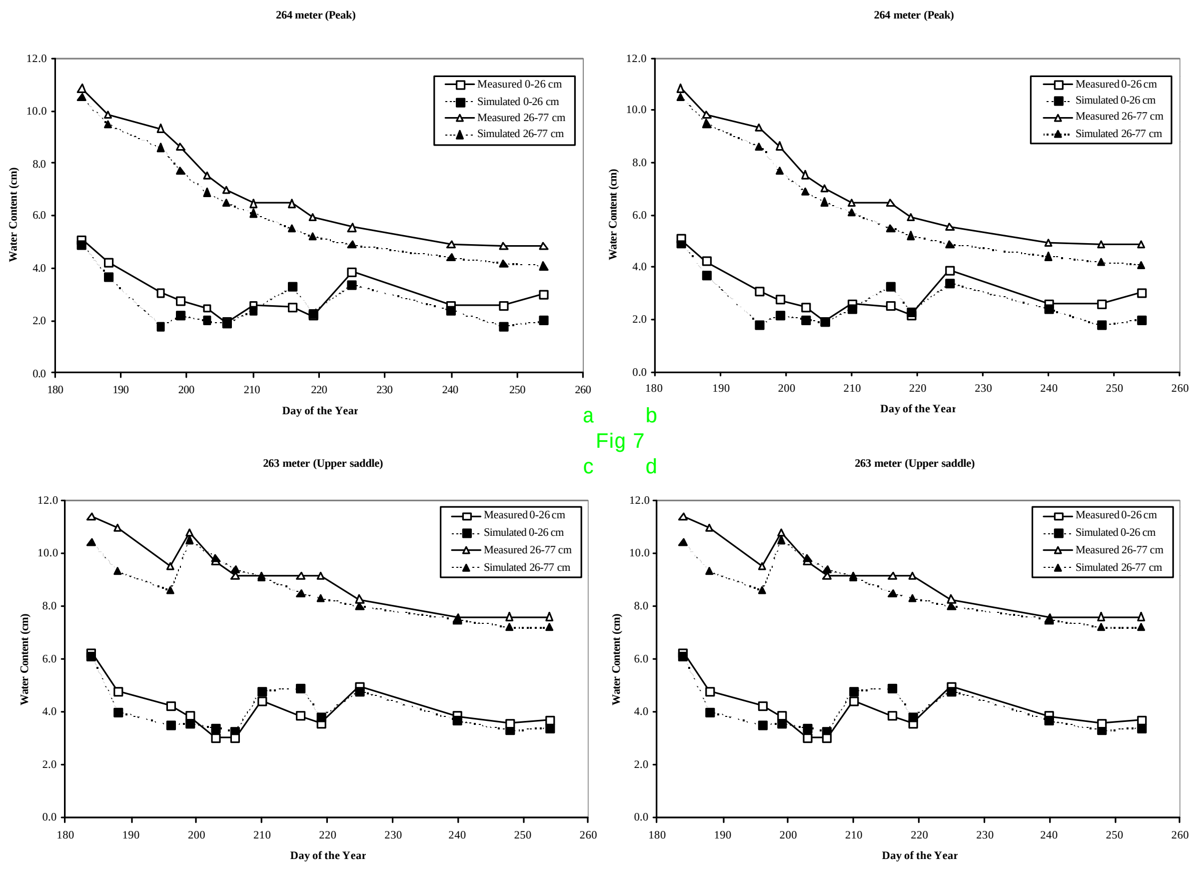


Fig 7

Conclusions

This paper discusses the application of TERRAE-SALUS, a digital terrain model with a functional spatial soil water balance model, at a field scale to simulate the spatial soil water balance and how the terrain affects the water routing across the landscape. 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 TERRAE-SALUS 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.

References

Basso, B. 2000. Digital Terrain Analysis and Simulation Modeling to Assess Spatial Variability of Soil Water Balance and Crop Production. Ph. D. Dissertation. Michigan State University. East Lansing. MI.

Gallant, J.C. 1999. TERRAE: A new element network tool for hydrological modelling. Second Inter-Regional Conference on Environment-Water: Emerging Technologies for Sustainable Water Management, Lausanne, Switzerland, 1-3 September 1999.

Ritchie, J.T. 1998. Soil water balance and plant water stress. In: G.Y. Tsuji, G. Hoogenboom, and P.K. Thornton (eds.), Understanding Options for Agricultural Production, pp. 41-54. Kluwer in cooperation with ICASA, Dordrecht/Boston/London.