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Runoff estimation in southern Brazil based on Smith's modified model and the Curve Number method

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ABSTRACT

The objective of this work was to measure and model the runoff for different soils classes at different rainfall intensities (30, 60 and 120 mm h^{-1}) in Southern Brazil. A portable rainfall simulator with multiple nozzles was used to simulate these rainfall intensities. For each soil, the initial time and runoff rate, rainfall characteristics (total, duration and intensities), surface slope, crop residue amount and cover percentage, soil densities (bulk and particle), soil porosity (bulk, macro and micro), textural fractions (clay, silt and sand), and the initial and saturated soil water content were measured. The runoff measured was compared to Smith's modified and Curve Number (USDA-SCS) models. The cumulative runoff losses were 67, 45 and 27% of the total rainfall, for a Rhodic Paleudalf, Typic Quartzipsamment and Rhodic Hapludox, respectively. An inverse relationship was observed between initial runoff and the runoff rate, independently of the soil surface and rainfall conditions. Increasing rainfall intensity decreased the time to runoff and increased runoff rate. The Smith's modified model overestimated the cumulative runoff by about 4%. The Smith's modified model presented a better estimate for both higher and lower rainfall intensities (120 and 30 mm h^{-1}). The SCS Curve Number model overestimated the cumulative runoff by about 34%. This large overestimate is probably due to that the model did not take into account the soil tillage system used in the field by farmers, particularly for irrigated conditions. The combination of high porosity, low bulk density and presence of crop residue on soil surface decreased runoff losses, independently of the soil texture class. Smith's modified model better estimated the surface runoff for soil with a high soil water content, and it was considered satisfactory for Southern Brazil runoff estimations. The SCS Curve Number model overestimated the cumulative runoff and its use needs adjustments particularly for no-tillage management system.

1. Introduction

The surface runoff corresponds to the segment of the hydrological cycle related to water movement over the soil surface. When rainfall intensity exceeds the soil infiltration rate, it begins to accumulate superficially, surpassing the water retention capacity on the land surface, and starts runoff. For Derpsch (1991), if the total rainfall amount that reached the soil surface could infiltrate, runoff would be zero and no contribution direct to the rivers would occur. In general, under constant rainfall intensity, infiltration and runoff rates are antagonistic processes, as one decreases (infiltration) the other increases (runoff), until they reach a certain constant value. This condition, when runoff rate practically does not vary with time, becomes known as steady state runoff.

According to Pruski et al. (2003), the factors that influence infiltration, also interfere with the resulting runoff. Runoff tends to increase with the increase in rain intensity and duration. Soil land use and cover greatly affects infiltration, and also has an important influence on raindrop interception. Increasing the percentage of plant canopy, residue cover, soil surface roughness, and the crop evapotranspiration, will increase infiltration rate at the beginning of the rainfall event, thus reducing runoff.

However, a large area and a steep watershed increase maximum flow of runoff that is measured at an outlet section. Besides, the more rounded the watershed shape, the faster will be the runoff concentrated and consequently, the greater the measured maximum flow. The land slope inclination is another factor that strongly influences soil and water losses because, as it increases, the greater the runoff volume and flow speed, resulting in less water infiltration. As a consequence, there is an increase in soil particles transport capacity by runoff, and increased capacity for soil disaggregation, by shear stress action, when water flow concentrates in furrows in downhill direction (Cogo et al., 2003).

The effective rainfall is one of the basic elements to take in account in a water balance model to effectively determine crop irri-

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Table 1
Information of location, soils, geographical coordinates and elevation of the places used for simulated rainfall events in Rio Grande do Sul.

City	Place	Soil	Latitude S	Longitude W	Altitude
Santa Maria	UFSM	Rhodic Paleudalf	29°43′10″	53°43′04″	101 m
Santo Augusto	Agropecuária Zamboni LTDA	Rhodic Hapludox	27°52′56″	53°45′42″	538 m
São Francisco de Assis	Agroantoniazzi	Typic Quartzipsamments	29°36′10″	55°19′10″	135 m

UFSM, Universidade Federal de Santa Maria.

gation requirements, thus having a fundamental role in irrigation planning, water resources efficiency and irrigation systems design (Romero and Graña, 1999). According to Silva et al. (1994), for an adequate irrigation management system, the amount of water that needs to be applied to the crop is the difference between the crop evapotranspiration and the effective rainfall. Several factors influence the effective fraction of the total rainfall, which can act separately or interact with each other. Any factor that affects infiltration, runoff or crop evapotranspiration, has influenced the percent of the effective rainfall. The effective rainfall determination is fundamental in rainfall studies in agriculture, because this portion of the rainfall directly contributes to soil available water. Thus, a more precise determination or estimation of the runoff is essential for the understanding and quantification of this hydrological process. Reliable studies with natural rainfall requires years of data collection to obtain a representative sampling of varying rainfall events. Besides, the rainfall irregularity nature makes the data collection difficult and replication almost impossible.

Due to this reason, rainfall simulators have been used to conduct studies in shorter periods and with a better control of rainfall intensity and duration (Silva et al., 2001). Several methods are used to evaluate runoff. The Soil Conservation Service, USDA, known as Curve Number method, uses the daily total precipitation, some characteristics of water infiltration, land use and agricultural practices.

The model of Smith (1972) was developed based on the equation of Richards (1931), and takes in account that runoff begins as soon as the water is ponding on the soil surface. However, at field conditions, usually this does not happen due to the soil surface roughness and surface covering, that delay the runoff beginning. Based on these reasons, Cabeda (1980) substituted the water ponding time by the initial runoff time.

The objective of this work was to determine and model the runoff in soils with different physical characteristics (soil texture, porosity, bulk density, water retention capacity, infiltration capacity, soil slope, percentage of soil cover), using different rainfall simulated intensities (30, 60 and 120 mm h^{-1}) in the Rio Grande do Sul state, Brazil.

2. Materials and methods

This work was carried out in three locations in Rio Grande do Sul (Table 1 and Fig. 1). The simulated rainfalls were applied using a portable simulator with multiple 80–100 Veejet oscillating nozzles, installed at 2.45 m above the soil surface with water pressure for the nozzles kept at 41.4 kPa. In each soil three rainfalls intensities (30, 60 and 120 mm h^{-1}) were applied. These values were based on rainfall intensities observed in the region and also because these values will be used for further studies of soil and water losses of irrigated areas. For each application of simulated rainfall, six plots (1.0 m × 0.5 m) were delimited using metal borders inserted at least 10 cm into the soil, containing a runoff collector at the bottom. A second rainfall was applied at the same spot, 24 h after the first.

The runoff starting time was determined when a continuous thread of water began to flow in the runoff collector and the soil surface had pounded water. During the rainfall, runoff was measured every 5 min. The runoff volume was measured until a constant value was observed in two consecutive determinations or until the end of rainfall application (120 min). The soil steepness for all plots was measured at each location.

The percentage of soil cover by crop residues was determined by the square points counting method (Mannering and Meyer, 1963), using a 72 square grid, and counting the number of grid intercepts with and without surface residue below, the fraction between them was the percent cover. The dried mass of superficial crop was determined by sampling three areas of 0.25 m^2 randomly. Samples were kept in an oven at 65 °C until obtaining a constant mass. The region climate is classified as "Cfa", subtropical humid, according to Köppen's climatic classification (Moreno, 1961). In this class, the average temperature of the hottest month is higher than 22 °C and the minimum temperature of the coldest month oscillates between −3 and 18 °C. The average annual rainfall varies from 1322 to 1769 mm.

The soils sites were managed for five consecutive years with no-till. In the last two years the crop rotation used was black oat/soybean/wheat/corn. The black oar was cultivated before the installation of the experiment. When rainfall simulation began, black oat was at blooming stage. Before the application of each simulated rainfall, the gravimetric soil water content was determined by collecting soil samples at 0–10 cm depth and measuring mass before and after drying to 110 °C.

In an adjacent undisturbed area, soil samples were collected at a 0–10 cm depth for determinations of total porosity, macroporosity, microporosity and soil bulk density. Three disturbed soil samples were collected at the same depths for texture and particle density determinations. The soil particle density, bulk density and porosity determinations were performed using the methodology described in EMBRAPA (1997). The pipette method was used for texture (Gee and Bauder, 1986). Soil particle density was obtained using the balloon volumetric method and bulk density by collecting ring soil samples with a volume of 65 cm^3. The volumetric soil water content at saturation and at a matric potential of −0.006 MPa was used to define soil total porosity and microporosity, respectively. The macroporosity was calculated by the difference between the total porosity and microporosity.

The Smith's mathematical model was used to describe the runoff (Alves and Cabeda, 1999), and the soil water infiltration based on modifications presented by Alves and Cabeda (1999):

$$i = (R - i_c) \times \left(\frac{t_e}{t}\right)^b + i_c, \quad \text{for } t > t_e \qquad (1)$$

where, i is the infiltration rate at a time t (mm h^{-1}); R is the constant rainfall intensity (mm h^{-1}); i_c is the infiltration constant rate (mm h^{-1}); t_e is the time when runoff starts (min); t is the time after runoff starts (min) and b is a dimensionless parameter for model adjustment.

Infiltration and runoff are antagonistic processes: as the former increases, the latter will decrease in the same magnitude (under constant rainfall intensity). So, the following modifications were introduced in the model: (i) the term $R - i_c$ was substituted by the constant runoff rate (e_c) in mm h^{-1}; (ii) subtracting the expression $(t_e/t)^b$ from one; and (iii) excluding the term i_c in Eq. (1), which