Nordic Hydrology, 31 (1), 2000, 15-26

Large Scale Basins With Small to Negligible Slopes

Part 1: Generation of Runoff

Luis Silveira

Dept. of Fluid Mechanics and Environmental Eng., School of Eng.
University of the Republic, Montevideo, Uruguay
Div. of Hydraulic Eng.,
Royal Institute of Technology, Stockholm, Sweden.

In the first of this two-paper series, the main mechanisms for generation of runoff from rainfall in large basins with small to negligible slopes are analyzed using available data from the Río Negro basin in Uruguay. Topography and soils were examined in order to identify physical features that may influence the flow patterns. Soil moisture storage in space and soil moisture variability in time were also evaluated to relate rainfall and runoff generation. The study revealed the existence of strongly developed horizontal layers. Soil moisture depends essentially on vertical water transport processes due to the low morphological energy of the terrain. Surface and subsurface flow occurs during the season of low evapotranspiration where soils become progressively wet. Extreme storms in terms of accumulated rainfall are required to produce surface and subsurface flow during the season of high evapotranspiration. In the following paper, these observations and hypotheses are used to model a large basin with small to negligible slopes.

Introduction

Topography, soil and its vegetative cover are essential in generation of runoff from a given basin. However, most hydrological research related to hydrological runoff mechanisms are concerned with small (less than 1 km^2 and up to 10 km^2) hillslope basins; consequently large basins, specially with gentle reliefs, are rarely considered (Burt 1989).

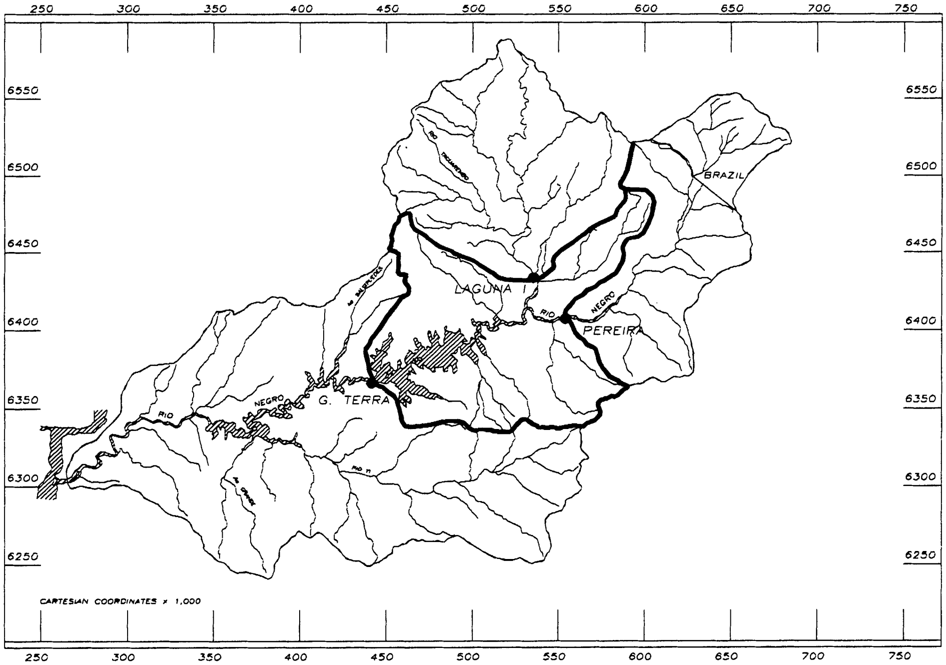

Fig. 1. The study area within the Rio Negro basin in Uruguay.

This paper analyzes the flood response of large basins characterized by small to gentle undulating slopes mainly covered with natural grasslands. Soil profiles were analyzed in order to identify features that may influence the flow patterns. Changes of soil moisture storage in space and antecedent soil moisture in time were also analyzed to relate rainfall and runoff generation.

The widely used hydrological classification of soils developed by the U.S. Soil Conservation Service (Mockus 1964; Rawls *et al.* 1993), hereafter referred to as SCS, was adopted with the purpose of grouping and to simplifying the available physical data.

Study Area and its Characterization

The study area was set up in Uruguay, the only country in South America entirely within the temperate zone. Three sub-basins within the Río Negro basin were selected. These sub-basins are the main tributaries to the reservoir of the Gabriel Terra hydropower station: 1) Pereira at the Río Negro, 2) Laguna I at the Río Tacuarembó, and 3) the incremental basin up to the dam as shown in Fig. 1. The total area covered by these three sub-basins is 39,320 km^2. An extension of about 2,900 km^2 is found in Brazil. Table 1 shows the surface areas covered by each sub-basin.

Table 1 – Slopes of sub-basins and main rivers in the study area

Basin	River	Area (km2)	Basin (%)	Average slopes Classification	River (‰)
Pereira	Negro	11,354	0.76	Very smooth	0.26
Laguna I	Tacuarembó	13,945	0.94	Very smooth	0.32
G. Terra	Negro (Reservoir)	14,021	0.75	Very smooth	0.03

The study area is sparsely populated. Its prevailing landscape is gently undulating with a horizon ever remote. Land cover is mainly natural pasture intercepted by riparian woodland along the rivers. The combination of its gentle topography, humid subtropical climate, native vegetation and plentiful water, supports considerable cattle-raising activities. The existing artificial forest in the Río Negro basin is related to livestock needing protection from the wind and shadow. This artificial forest is integrated into the landscape as spots and wind curtains. Artificial forestation for wood production is still insignificant. Agricultural activities such as maize and potatoes as well as pisciculture are also minor in the whole basin. However, since the last decade the rice plantation is increasing in the study area and subsequently even the construction of small to medium earth dams for irrigation. Nevertheless, the maximum dammed volumes are still less than 3% of the maximum volume of about 12,300 Hm^3 stored by the Gabriel Terra dam.

Topography of the study area is very smooth. Table 1 shows the average slope of each sub-basin computed according to the methodology developed by Horton (1914) and the average slopes of the main rivers as calculated by the methodology of Taylor and Schwartz (1952). The selected sub-basins are topographically similar as shown in Fig. 2, which represents its hypsographic curves.

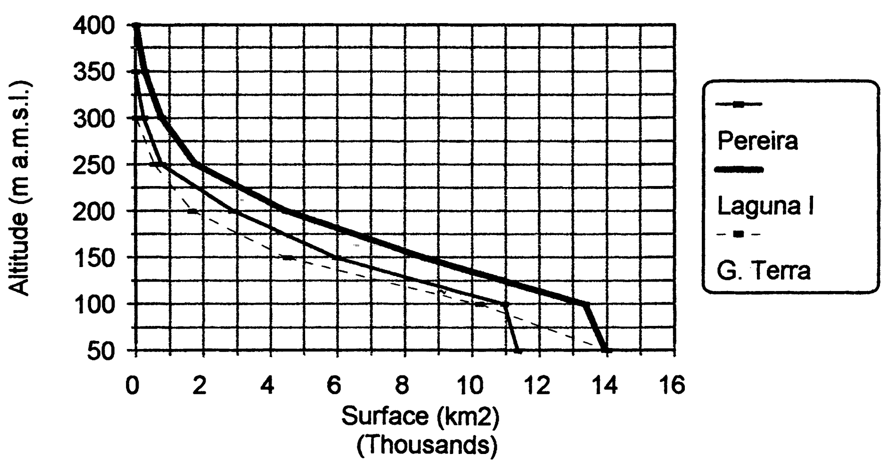

Fig. 2. Hypsographic curves.

Climate is humid subtropical. Annual rainfall is around 1,000 to 1,400 mm/year relatively evenly distributed through the year. Mean annual evaporation is around 800 to 1,000 mm/year ranging between 50 mm/month during the winter and up to 250 mm/month during the summer. Mean average runoff coefficient is about 0.35. Open aquifers are limited whereas deep confined aquifers are dominant in the study area.

Hypothesis About Runoff Generation in Large Basins With Gentle Reliefs

Runoff generation in large basins with gentle reliefs depends on main physical factors such as: a) topography and its influences in the process of soil formation b) spatial variations of soil moisture storage capacity and c) changes of antecedent soil moisture in time.

The movement of water on and through the soil is significant in the active process of soil formation and development of horizontal layers known as A-, B- and C-horizons. This movement is partly controlled by topography. Surface runoff and erosion are commonly high in hillsides with steep slopes, while the fine sediment transported downward through the soil profile is limited due to an often low infiltration rate (Marchesi and Durán 1969; Wen Shen and Julien 1993). Under these conditions, the soil is commonly shallow and the horizontal layering is slightly developed. Reversely, in catchments with gentle reliefs, the soil is normally deeper and the horizontal layering is strongly developed. A significant quantity of clay is transported downward due to a usually high infiltration rate, resulting in a B-horizon generally much more heavy than the soil texture of the A-horizon. Assuming these conditions, the percolation to deeper soil layers is controlled by the B-horizon as follows: When the B-horizon is dry, its high clay content causes the formation of preferential flow paths which allow rapid downward movement of water when the wetting front produced during a storm reaches the B-horizon. Afterwards, when the B-horizon becomes wetted, the clay expands and closes the vertical preferential flow paths. Then, the B-horizon may become an essentially impervious layer and, consequently, the percolation to deeper soil layers is controlled by the hydraulic conductivity of this horizon. Maxey (1964) already noted that the A-horizon may become saturated during appreciable periods due to the effect of limited percolation through the B-horizon.

The hypotheses of decreasing hydraulic conductivity with depth and essentially impervious B-horizons confine the soil moisture storage essentially to the A-horizon.

Soil moisture condition of soils depends essentially on vertical water transport processes due to the low morphological energy of the terrain. Soil normally stores water in months where monthly evapotranspiration is low and releases water through evapotranspiration in months where evapotranspiration is high. During the season of low evapotranspiration the soil becomes progressively wet and reaches saturation or near saturation state. Smaller amounts of rain falling over wet soils are needed to produce both surface and subsurface runoff. Reversely, during the season of high evapotranspiration the soil dries and rainfall normally infiltrates and afterwards is evapotranspirated before significant flow runoff may occur. Rains of high intensity or significative rainfall amounts which produce saturation of the A-horizon are necessary to generate significative surface and subsurface runoff during the season of high evapotranspiration.

Similar soil water patterns in temperate regions of Australia where hydraulic conductivity decreases with depth were described by Grayson *et al.* (1997). They distinguished two preferred states of soil water patterns: the wet and the dry state. The first is dominated by lateral water movement through both surface and subsurface paths whereas the second is dominated by vertical fluxes, depending on soil properties. These two states are similar to our observations about seasons of low and high evapotranspiration. Nevertheless, in their study the topography upslope is the dominant control on spatial patterns of thickness of the A-horizon, soil moisture and wet areas generating surface runoff. The study catchments are, however, about 1 km^2 with steep slopes of about 11 to 14%.

Methodology

The methodology followed is:

- Verify the statements regarding the relationship between a gentle topography and soil profiles with strongly developed horizontal layers and high clay content of the B-horizon. The following information was available: a) a classification of soils for agricultural purposes, by which the whole country is divided into ninety-nine geographical units according to its morphological soil profiles, physical and chemical characteristics (Doti *et al.* 1979) and b) a classification of these ninety-nine soil units into the four hydrological groups according to the widely used classification developed by the SCS (Durán 1995). Based on this information, the geographical units and the corresponding soil profiles within the study area were identified in this study in order to find the thickness of the A- and B-horizon and its clay content. Soil profiles were then grouped according to the SCS in order to simplify the information.
- Analyze the spatial variability of soil moisture storage. The available information was a report correlating the available water (the difference between field capacity and wilting point) in the upper A-horizon and the geographical soil units (Alvarez *et al.* 1989). Geographical soil units found in Pereira, Laguna I and the incremental basin up to the Gabriel Terra dam were arranged in an ascending sequence according to their available water capacity.

Correlate changes of antecedent soil moisture in time with accumulated rainfall during the storms. The available data was daily rainfall *P*, streamflow *Q* and potential evapotranspiration *ETP* from Laguna I and Pereira sub-basins. Then, a simple hydrological water balance similar to the model developed by Thornthwaite and Mather (1955) was applied to compute daily soil moisture. Daily actual evapotranspiration *ETR* is computed depending on whether daily rainfall *P* is greater or less than potential evapotranspiration *ETP*

$$P > ETP \qquad ETR = ETP \tag{1}$$

$$P \leq ETP \qquad ETR = \min(P+S_{i-1}, ETP) \tag{2}$$

where S_{i-1} is a state variable representing the soil moisture content the day before.

Changes in soil moisture content ΔS depend on the relationship between daily rainfall and the losses (actual evapotranspiration *ETR* and measured runoff *Q* or effective rainfall $P_e = Q/A$, where *A* represents basin area). Thus

$$\Delta S = P - ETR - P_e \tag{3}$$

Daily soil moisture content is then computed as

$$S_i = S_{i-1} + \Delta S \tag{4}$$

Results

Thirty-nine geographical units were identified. Its soil profiles described in Doti *et al.* (1979) were analyzed. Only soils from groups B, C and D could be identified. Minimum (Min), maximum (Max) and average (Avg) thickness and clay content of the A- and B-horizons for each soil group and sub-basin are shown in Table 2. It proves – for this particular case of basins with gentle reliefs – that the average clay content in the B-horizon is always higher than the average clay content of the A-horizon. The B-horizon is thicker than the A-horizon, normally about twice the A-horizon.

Fig. 3 represents the cumulative distribution function of available water capacity. Available water capacity is higher in Pereira sub-basin than in Laguna I and G. Terra sub-basins, and varies from about 30 mm up to 160 mm. Fig. 3 also shows that the available water capacity is high for most soils, *i.e.*, higher than 70 mm for about 90% of the soils within Pereira. The respective figures for Laguna I and G. Terra are 60 and 50 mm.

The problems encountered during the application of the simple water-balance model were the following: a) soil moisture storage must be assumed infinite, since soil moisture is the unknown, and b) the hydrological water balance does not take into account runoff travel time and channel storage, which must be considered as observed by Thornthwaite and Mather (1955). The combination of both constraints

Table 2 –Thickness and clay content of the A- and B-horizons

Basin	Soil group (SCS)	Area (km2)	Area (%)	A-horizon Thickness (cm) Min	Max	Avg	A-horizon Clay (%)	B-horizon Thickness (cm) Min	Max	Avg	B-horizon Clay (%)
Pereira	B	1,577	19	20	80	31	21	45	100	77	43
	C	3,178	37	17	44	29	28	25	65	39	46
	D	3,733	44	5	65	32	28	40	60	49	43
Laguna I	B	3,135	22	15	110	54	16	45	140	114	48
	C	6,350	46	20	60	47	13	25	120	87	32
	D	4,460	32	3	30	24	26	55	81	55	44
G. Terra	B	3,909	28	20	80	32	24	15	100	61	46
	C	4,167	30	10	60	34	19	5	130	70	47
	D	5,945	42	3	30	22	37	15	60	46	53

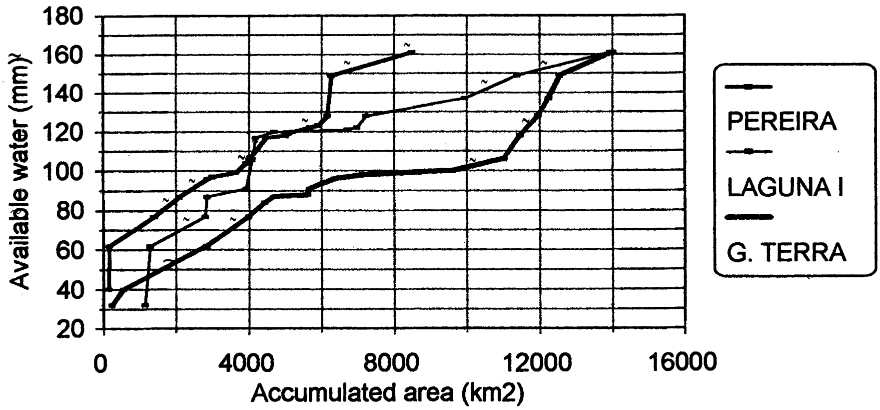

Fig. 3. Cumulative distribution function of available water capacity.

may produce single peak values of soil moisture that are not possible in reality. Nevertheless, the overall result gives an idea about changes of soil moisture with time and storm size. The simple water balance was computed for the 15-year period between 1975 and 1989. Available data were daily rainfall data measured in 37 non-recording raingauges uniformly distributed inside the study area, measured streamflow at Pereira and Laguna I streamgauges and pan evaporation observed close to the Gabriel Terra hydropower station. As an example, Figs. 4 and 5 show daily soil moisture storage in Pereira and Laguna I sub-basins during 1987 and 1988 as simulated by the simple water-balance model.

An examination of Fig. 4 shows that soil moisture storage in the Pereira sub-basin is normally between 0 and about 30 mm during spring and summer (approximately

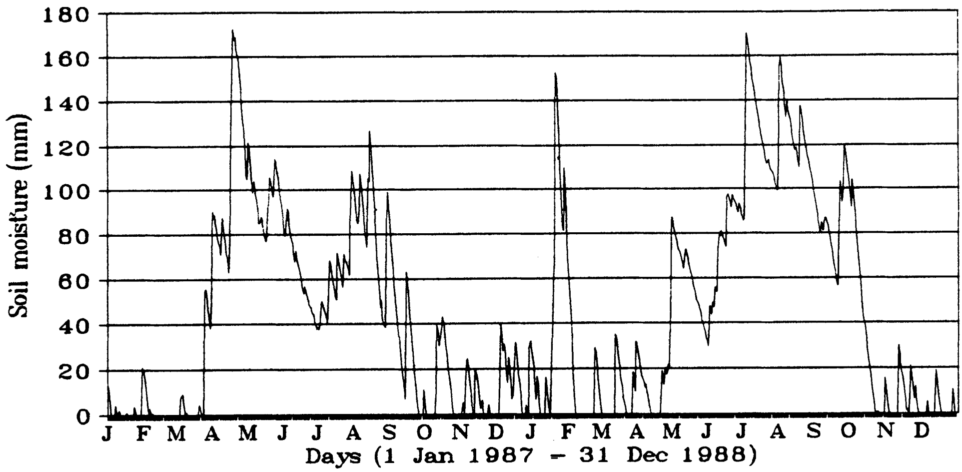

Fig. 4. Daily values of soil moisture storage in the Pereira sub-basin simulated by a simple water balance model.

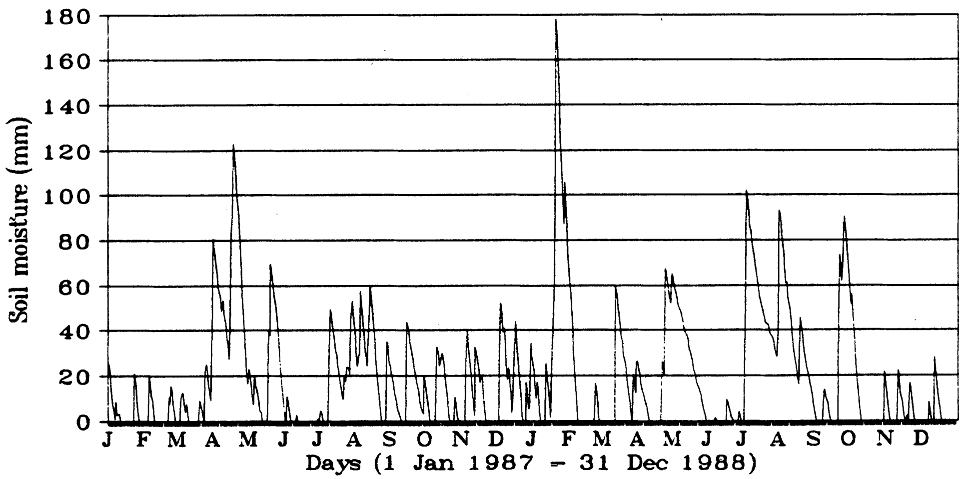

Fig. 5. Daily values of soil moisture storage in the Laguna I sub-basin simulated by a simple water balance model.

from October to March) due to high evapotranspiration. Then, soil moisture content increases during autumn and winter (approximately from April to September) when evapotranspiration decreases, which is reasonable for deep soils mainly covered with natural pastures, in areas where the climate is humid subtropical. Peak values of soil moisture represent extreme storms regarding accumulated rainfall, *i.e.*, a 4-day storm in April 1987 where accumulated rainfall was 127 mm, 186 mm during a

5-day storm in January 1988 and 92 mm during a 3-day storm in July 1988.

A similar examination of Fig. 5 shows that soil moisture storage is normally between 0 and about 40 mm during spring and summer. Then, soil moisture content increases during autumn and winter. Peak values of soil moisture represent extreme storm sizes, *i.e.*, a 4-day storm in April 1987 where accumulated rainfall was 112 mm, 212 mm during a 5-day storm in January 1988 and 110 mm during a 2-day storm in July 1988.

Annual rainfall in Pereira was 1,446 mm in 1987 and 1,201 mm in 1988, and in Laguna I 1,332 and 1,098 mm/year, respectively. Statistically, the mean monthly rainfall is about 100-120 mm every month and the number of rainy days is about five or six per month. However, in any month the accumulated rainfall may range between zero and up to around 450 mm/month. Therefore, normally it cannot be expected that soil moisture reaches saturation during a single storm except for the most extreme storms as suggested by the analyses of Figs. 4 and 5. Convective storms of short duration and high intensity normally occur during summer, while frontal storms of large duration and lower intensity prevail during winter.

Fig. 6 shows catchment rainfall and runoff in the Pereira sub-basin. During January to March 1987 no significant runoff is observed, probably due to dry soils and high evapotranspiration. The first significant runoff is observed at the end of April 1987, which was produced by a 4-day storm that occurred between 16 and 20 April, where accumulated rainfall was 127 mm. The peak observed in the middle of August 1987, during the winter, was produced by eight small storms, which probably produced saturation of the soil due to low evapotranspiration and high accumulated rainfall of 170 mm. Low runoff between October 1987 and April 1988, spring and summer, was due to high evapotranspiration. Significant runoff observed at the beginning of February 1988, during the summer, was produced by a 5-day storm where accumulated rainfall was 186 mm. The peaks observed between July and October 1988 were produced by significant storms in terms of accumulated rainfall. During spring 1988 runoff was again low due to high evapotranspiration.

The relationship between average rainfall and runoff in the Laguna I sub-basin shows a similar trend as that observed for the Pereira sub-basin (Fig. 7). During the summer 1987, January to March, no significant runoff is observed. The first important response to a rainstorm is observed at the end of April 1987, which was produced by a 4-day storm, where accumulated rainfall was 112 mm. The hydrograph observed at the end of May 1987, during autumn, was produced by a 4-day storm where accumulated rainfall was 81 mm. During winter, where evapotranspiration is low and it is more likely to achieve saturation of the soil, thirteen rainy days between the end of July and the middle of August produced significant runoff. Accumulated rainfall was 197 mm.

Runoff was again low during spring and summer, September 1987 to April 1988, as evapotranspiration increased. The hydrograph observed at the beginning of February 1988, during summer, was produced by a 5-day storm where accumulated

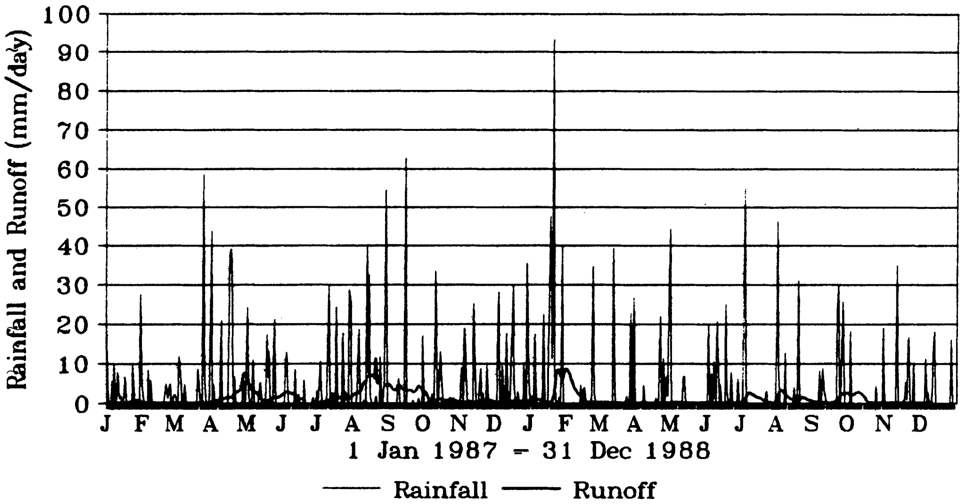

Fig. 6. Catchment rainfall and runoff in the Pereira sub-basin.

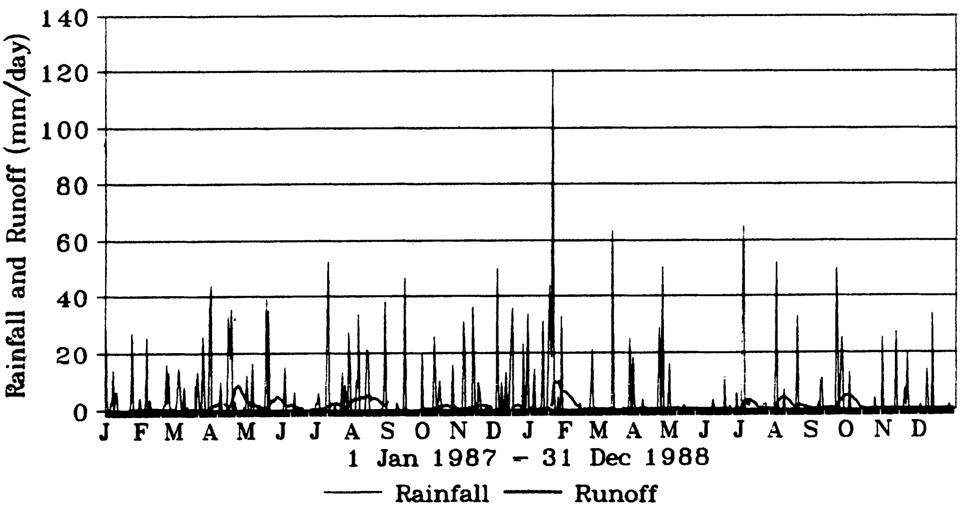

Fig. 7. Catchment rainfall and runoff in the Laguna I sub-basin.

rainfall was 212 mm. No significant runoff is observed after the 1-day storm observed in March 1998, where accumulated rainfall was 64 mm. However, the antecedent rainfall was zero during the 16 days prior to the storm. The hydrographs observed between July and October 1988 were produced by significant storms in terms of accumulated rainfall. During the end of spring, November and December 1988, runoff was once again low.

Summary and Conclusions

Generation of runoff from rainfall in large basins with small to negligible slopes was analyzed using available data from the Río Negro basin in Uruguay and a simple water-balance model. The data consisted of main physical information affecting runoff generation as topography, soil profiles and soil moisture storages and daily rainfall and runoff records.

Soils are moderately well to well-drained soils, deep and permeable. The analysis of soil profiles revealed the existence of strongly developed horizontal layers and an essentially impervious B-horizon due to high accumulated clay content transported downward by infiltration.

The maximum water storage of the A-horizon is significantly high in terms of normally expected rainfall. Computation of daily soil moisture storage revealed that the moisture condition of soils depends essentially on the relationship between rainfall and evapotranspiration. Soils normally store water between April and September, where monthly evapotranspiration is low and dries through evapotranspiration between October and March, where monthly evapotranspiration is high. Rains of high intensity or significative rainfall amounts which produce saturation of the A-horizon are necessary to generate subsurface and surface runoff during the season of high evapotranspiration. Runoff depends just on the antecedent soil moisture condition representing the rate of wetness.

Under these conditions, the annual runoff coefficient is low (0.3 to 0.35) in large basins with small slopes in the temperate zone. Runoff mechanisms are similar to those observed in small hillslope basins. However, the weight of vertical fluxes (rainfall, infiltration and evapotranspiration) increases due to the low morphological energy of the terrain.

Further research considering other large basins with similar characteristics is required to confirm the observations above and to develop tools to predict runoff generation, delay time and base time of hydrographs.

References

Alvarez, C., Cayssials, R., and Molfino, J. H. (1989) Estimación del almacenaje de agua en las tierras del Uruguay (Estimation of soil moisture storage in Uruguay). Available from: Ministerio de Ganadería, Agricultura y Pesca. Dirección de Suelos y Aguas. Avda. Garzón 456. C. P. 11800 Montevideo, Uruguay (In Spanish).

Burt, T. P. (1989) Storm runoff generation in small catchments in relation to the flood response of large basins, in Beven, K., and Carling, P. (eds), *Floods: Hydrological, Sedimentological and Geomorphological Implications*, John Wiley & Sons. Ltd.

Doti, R., Durán, A., and López Taborda, O. (1979) Carta de Reconocimiento de Suelos del Uruguay. Vol. III (Soil Recognition Map of Uruguay. Vol III). Available from: Ministerio de Ganadería, Agricultura y Pesca. Dirección de Suelos y Aguas. Avda. Garzón 456. C.P. 11800 Montevideo, Uruguay (In Spanish).

Durán, A. (1995) Clasificación en grupos hidrológicos de los suelos del Uruguay. (Classification of Uruguay's soils into hydrological groups). Available from: Facultad de Agronomía. Area de Suelos y Aguas. Cátedra de Edafología. Avda. Garzón 780. C. P. 11800 Montevideo, Uruguay (In Spanish).

Grayson, R. B., Western, A. W., Chiew, F. H. S., and Blöschl, G. (1997) Preferred states in spatial soil moisture patterns: Local and non-local controls, *Water Resources Research, Vol. 33 (12)*, pp. 2897-2908.

Horton, R.E. (1914) Derivation of runoff from rainfall data. Discussion, *Trans. Am. Soc. Civil Engrs., Vol. 77*, pp. 369-375.

Marchesi, E., and Durán, A. (1969) Suelos del Uruguay (Uruguay's soils), *Nuestra Tierra*, Vol. (18), Montevideo, Uruguay (In Spanish).

Maxey, G. B. (1964) Hydrogeology in Chow, V. T. *Handbook of Applied Hydrology*, McGraw-Hill Book Company.

Mockus, V. (1964) *National Engineering Handbook. Section 4 – Hydrology*, U.S. Department of Agriculture (U.S.D.A.)

Rawls, W. J., Ahuja, L. R., Brakensiek, D. L., and Shirmohammadi, A. (1993) in Maydment, D. R. *Handbook of Hydrology*, McGraw-Hill, Inc.

Taylor, A .B., and Schwartz, H. E. (1952) Unit-hydrograph lag and peak flow related to drainage basin characteristics, *Trans. Am. Geophys. Union, Vol. 33*, pp. 235-246.

Thornthwaite, C. W., and Mather, J. R. (1955) The water balance. Publ. Climatol. Lab. Climatol. Drexel Inst. Technol., 8(1), pp. 1-104.

Wen Shen, H., and Julien, P. Y. (1993) Erosion and sediment transport in Maydment, D. R. *Handbook of Hydrology*, McGraw-Hill, Inc.

Received: 27 February, 1998
Revised: 7 October, 1998
Accepted: 3 May, 1999

Address:
Instituto de Mecánica de los Fluidos e Ingeniería Ambiental,
Facultad de Ingeniería,
Julio Herrera y Reissig 565,
C.P. 11300 Montevideo,
Uruguay,
Email: lesy@fing.edu.uy