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Large Scale Basins With Small to Negligible Slopes

Part 2: Hydrological Modelling

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.

Large basins with small to negligible slopes are seldom considered in the hydrological literature. An example of such basins is the Río Negro catchment in Uruguay. The first of this two-paper series showed the following special features: a) the existence of strongly developed horizontal layers and an essentially impervious B-horizon, b) significantly high soil moisture storage in terms of normally expected rainfall during a storm and c) the importance of vertical water transport processes to establish the soil moisture condition prior to a storm and its role concerning basin runoff response. These observations and hypotheses were taken into account by the lumped conceptual hydrological model called Hidro-Urfing through the percolation function and the basin runoff response function. This second paper shows its application to the Laguna I basin, a sub-basin of the Río Negro catchment with a surface area of 13,945 km^2, and its ability to model the major storm hydrographs without any subdivision into smaller sub-basins. Modelling of low flows requires disaggregation of spatial-scale issues. A hydrological model of the entire Río Negro catchment did not previously exist.

Introduction

As mentioned in the first of this two-paper series, most investigations about generation of runoff from rainfall reported in the hydrological literature are related to small (less than 1 km^2 and up to 10 km^2) hillslope basins. Large basins with small to negligible slopes, usually larger than 1,000 km^2, are seldom considered. The special distinguishing feature of these basins is the different weight of the hydrological processes compared with those observed in hillslope basins (Kovacs 1978, 1983; Fuschini Mejía 1983, 1994). An example in South America of large natural grasslands with small to negligible slopes is the region covered by Paraguay, the south of Brazil, the west of Argentina and Uruguay.

The objective of this second paper is to simulate the hydrological processes which are affected due to the low morphological energy of the terrain. Available data from the Laguna I basin in Uruguay were used for this purpose. In the first of this two-paper series, observations and hypothesis were stated from the analysis of these data and later used in this second paper to introduce appropriate changes on existing hydrological models to simulate the transformation of rainfall into runoff. The resulting model is called Hidro-Urfing. Examples of its application to the Laguna I basin are discussed. As a first approximation, this large basin with a surface area of 13,945 km^2 was modelled in only one step without any subdivision into smaller sub-basins. The final objective of this research about the hydrological processes in large basins with small slopes and their simulation is to improve the existing use of natural water resources of flat areas through the knowledge of its behaviour.

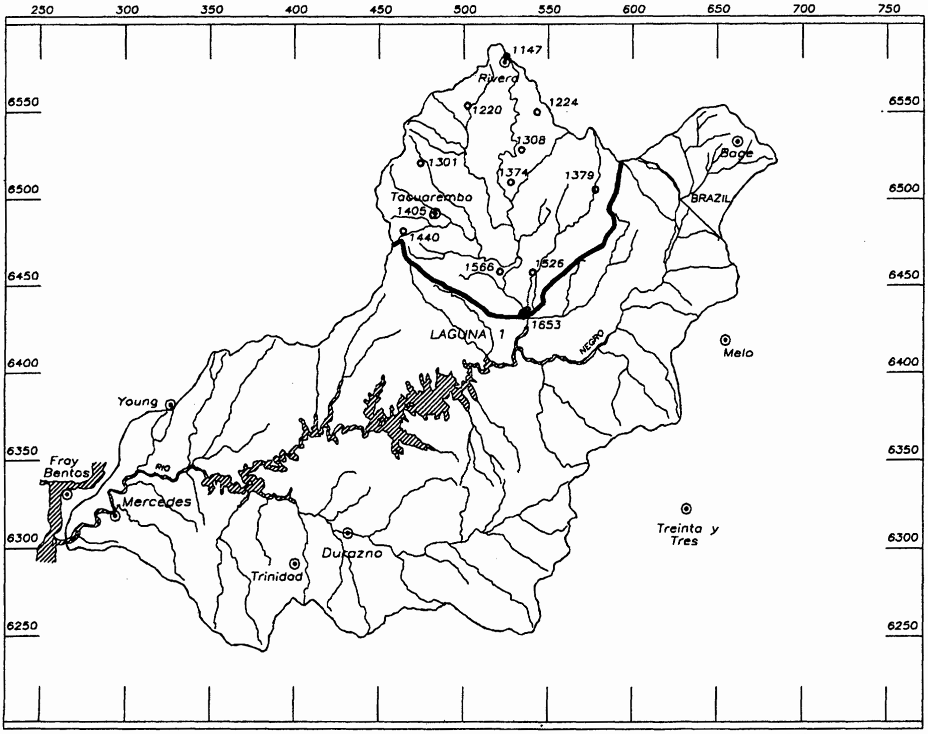

Fig. 1. The Laguna I basin within the Río Negro catchment in Uruguay.

Study Area and Available Data

The study area was set up in the Laguna I basin within the Río Negro catchment in Uruguay, as shown in Fig. 1.

The whole Río Negro catchment covers an extension of about 71,200 km^2, approximately one third of the country. Three hydropower stations located along this river produces about 3,000 Gwh representing about 60% of the country's hydropower energy. Hydropower generation depends mainly on management of large water volumes than on significative water falls. The Gabriel Terra hydropower station, located immediately downstream the Laguna I basin, was in 1945 the first dam constructed in a plain and its artificial lake was the biggest in the world. In spite of its importance, a hydrological model representing the relationship between rainfall and runoff of the entire Río Negro catchment did not previously exist.

The Laguna I basin has a surface area of 13,945 km^2. Its main river is the Río Tacuarembó which discharges into the Río Negro (Fig. 1). The northwest water divide consists of the Cuchilla Negra and the Cuchilla de Haedo, two mountain ridges with an altitude of about 250-400 m a.m.s.l. The prevailing landscape in the remaining area of the basin is gentle undulating with an average altitude of about 100-200 m a.m.s.l. Basin slope is 0.94% and the average slope of the Río Tacuarembó is 0.26 ‰. Basin and river slopes were computed according to the procedures developed by Horton (1914) and Taylor and Schwartz (1952), respectively. Soils are mainly covered with natural pastures intercepted by riparian woodland along the rivers. Its main land use is for livestock, where an estimated average load is 0.75 bovines and 3 sheep per hectare. Population is sparse (about 2.5 inhabitants/km^2). The main geological formations of the basin are essentially glacial sedimentary deposits. Climate is humid subtropical.

The available hydrometeorological data consist of daily rainfall, evapotranspiration and runoff records. Rainfall is measured at twelve nonrecording raingauges inside the basin. These gauges are listed in Table 1 and shown in Fig. 1. Mean monthly rainfall varies between 90 and 120 mm each month. Five to six usually non-consecutive rainy days are normally observed each month. Convective rains of short duration and high intensity prevail during the summer whereas frontal rains of large duration and low intensity are more common during the winter. Annual rainfall is

Table 1 –Nonrecording raingauges within the Río Tacuarembó basin in Uruguay.

Station	Place	X	Y	Station	Place	X	Y
1147	Rivera	524.0	6582.5	1379	Moirones	577.6	6504.0
1220	Tranqueras	503.0	6550.0	1405	Tacuarembó	482.5	6492.0
1224	Paso Ataques	542.0	6549.0	1440	Valle Edén	464.5	6480.0
1301	Paso del Medio	474.5	6520.0	1526	Picada de Coelho	541.0	6456.7
1308	La Calera	534.5	6527.0	1566	Cerro Cardozo	522.8	6456.0
1374	Minas de Corrales	531.0	6508.0	1653	Paso Laguna	536.2	6432.6

around 1,000 to 1,400 mm/year. Pan evaporation data is observed close to the reservoir. Monthly pan evaporation varies between 50 mm/month during the winter and up to 250 mm/month during the summer. Mean annual evaporation is around 1,000 mm/year. Streamflow is measured at Laguna I (Fig. 1). The streamgauge consists of vertical scales observed by local people. A field team from the electricity company makes periodical measurements of flow velocity in order to check and – if possible – to improve the existing rating curve. Streamflow measurements range approximately between 10 and 1,400 m^3/s. Mean average runoff at the basin outlet is about 150 m^3/s of which groundwater flow represents about 25 m^3/s according to flow measurements carried out during large dry periods.

Available physical information consists of topographical, geological, hydrogeological and soil maps as described in the first of this two-paper series.

Hydrological Processes in Large Basins with Gentle Reliefs

The special distinguishing feature of large basins with gentle reliefs is the low morphological energy of the system which modifies the weight of the hydrological processes depending on the local conditions of the region (Kovacs 1978, 1983; Fuschini Mejía 1983, 1994). The hydrological cycle is universal, but the weight of its components changes. Climate and morphology are the most decisive factors.

The study of available physical and hydrometeorological data from the Laguna I basin, developed in the first of this two-paper series, revealed the existence of: a) strongly developed horizontal layers and an essentially impervious B-horizon generated by high accumulation of clay transported downward by infiltration, and b) significantly high soil moisture storage in terms of normally expected rainfall amounts during a storm. The difference between field capacity and wilting point in the A-horizon is higher than 60 mm for about 90% of soils. Its average thickness is about 50 cm and its clay content about 15%. The average thickness of the B-horizon is about 100 cm and its clay content around 40 to 50%.

Previous research described by Silveira *et al.* (The antecedent soil moisture condition of curve number procedure, accepted for publication in *Hydrological Sciences Journal* in 1999) showed that the antecedent moisture condition of soils depends essentially on vertical water transport processes. Soil normally stores water between April and September, where monthly evapotranspiration varies between 50 and 100 mm and releases water through evapotranspiration between October and March, where monthly evapotranspiration is more than 100 mm and up to about 250 mm. During the season of low evapotranspiration the soil becomes progressively wet and reaches saturation or near saturation state as confirmed by field measurements with tensiometers. 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 is afterwards 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 significant surface and subsurface runoff during the season of high evapotranspiration. The analysis of the relationship between antecedent rainfall and potential evapotranspiration for natural pastures in the study region showed that a period of 15 days is required to explain a possible classification of the antecedent soil moisture condition prior to a storm. The corresponding period used by the US Soil Conservation Service (Mockus 1964; Rawls *et al.* 1993) is 5 days. The weight of infiltration and surface runoff depends just on the antecedent soil moisture condition representing dry, average and wet soils, and consequently also the hydrograph shape or in other words the basin runoff response. The scale-issue also arises in the context of the role of channel structures existing in large basins where channel storage and routing must also be considered (Burt 1989).

These observations were taken into account when developing the conceptual and lumped hydrological model called Hidro-Urfing through: a) the percolation function, which introduces a percolation coefficient to simulate the flow transport across the B-layer and b) the basin runoff response function, which uses a monotonic decreasing function to establish a relationship between antecedent accumulated rainfall and basin runoff response.

The Hidro-Urfing Model

Scarcity and uncertainty of input data due to data collecting networks and transmission equipments which are much more elementary than in developed countries are often a major constraint and a limiting factor in any hydrological study in developing countries. The difficulty to fulfil the input data requirements of distributed physically-based models often limits the selection of a hydrological model to a lumped conceptual model (Linsley *et al.* 1988).

The Hidro-Urfing model described in this paper is a lumped conceptual hydrological model mainly based on the Sacramento catchment model developed by the U.S. National Weather Service and the California Department of Water Resources (Burnash *et al.* 1973; Burnash 1995) and the HBV model developed by the Swedish Meteorological and Hydrological Institute (Bergström 1976, 1995). The model is the result of simplifications due to the scarce input data and the introduction of appropriate changes to describe the special distinguishing feature of runoff mechanisms in large basins with gentle undulating slopes mainly covered with natural grasslands. Its purpose is to simulate the transformation of a series of daily rainfall inputs to the resulting streamflow hydrograph at the basin outlet. A flow diagram of the Hidro-Urfing model is shown in Fig. 2. This flow diagram and the equations below uses the same notation as the Hidro-Urfing code. A more detailed description of the model is given by Silveira (1998).

Daily rainfall and potential evapotranspiration are the basic input data to the mod-

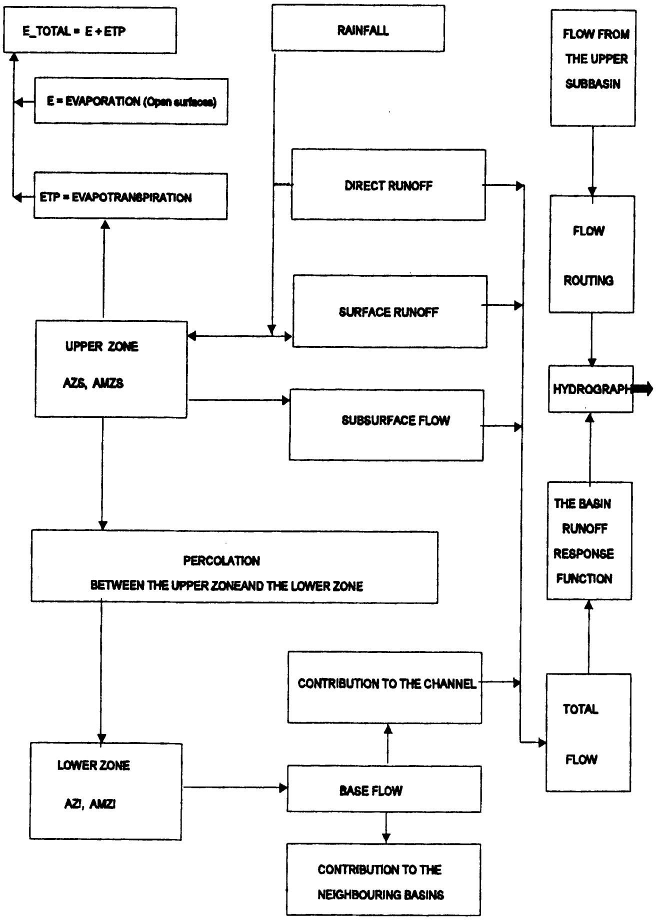

Fig. 2. Flow diagram of the Hidro-Urfing model.

el. Streamflow data measured at the basin outlet is used for calibration and verification.

Daily average rainfall is computed according to the Thiessen method. Since daily rainfall records are seldom complete, a procedure computes the average rainfall for the actual combination of nonrecording raingauges with and without data. Rainfall intensity is simulated dividing the day into a rainy portion and a dry portion. The relative length of the rainy portion is established through, *e.g.*, correlation equations relating accumulated daily rainfall and storm duration.

The model visualizes two storages: an upper zone storage and a lower zone storage. The upper zone storage coincides with the A-horizon and the lower zone storage with the C-horizon. The upper and the lower zone storages are linked by the B-horizon through the percolation function. Rain may fall over two basic areas: a) lagoons and impervious areas directly linked to the network of rivers and b) permeable areas. The first area produces direct runoff while the second area generates surface runoff when the upper zone storage reaches saturation (*i.e.*, field capacity minus wilting point). The upper zone yields subsurface flow depending on its water content and depletion coefficient. Likewise, the lower zone produces base flow. Soils and open water surfaces also releases water through evapotranspiration and evaporation.

The percolation function proposed by the Sacramento model (Burnash 1995) was adapted to introduce the percolation coefficient of the B-layer. The following limiting rates were distinguished:

a) If the lower zone is saturated, the model assumes that the percolation rate (*PERC*) is minimum and equal to the maximum base flow

$$PERC_{\min} \equiv AMZI \times KZI \tag{1}$$

where $PERC_{\min}$ is the minimum percolation rate, *AMZI* is the maximum water content of the lower zone and *KZI* is the depletion coefficient of the lower zone.

b) If the lower zone is completely dry and the upper zone is saturated, the model assumes that the percolation occurs at its maximum rate ($PERC_{\max}$), which is expressed as

$$PERC_{\max} = PERC_{\min}\,(1+x) \tag{2}$$

where x represents the difference between and $PERC_{\max}$ and $PERC_{\min}$.
The maximum percolation rate is also controlled by the percolation coefficient of the B-layer. Then it follows

$$PERC_{\max} \equiv AMZS \times KB \tag{3}$$

where *AMZS* is the maximum water content of the upper zone and *KB* is the percolation coefficient of the B-layer.
Eqs. (1), (2) and (3) yields

$$x \equiv \frac{AMZS \times KB}{AMZI \times KZI} - 1 \tag{4}$$

c) Percolation is proportional to i) the relationship between available water content of the upper zone and saturation and ii) the relationship between the existing deficit in the lower zone and saturation.

From the above it follows that percolation can be expressed as

$$PERC = PERC_{\min}\left(1 + x\,\frac{AMZI-AZI}{AMZI}^{\beta}\right)\frac{AZS}{AMZS} \tag{5}$$

where *AZS* and *AZI* represent the temporal water content of the upper and lower zone. The value of β produces changes of the percolation rate in a linear or exponential way.

Total runoff generated by the upper and lower soil zones is distributed on consecutive days by the basin runoff response function in order to simulate the travel time of a water drop to the basin outlet. This function is similar to the response function-proposed by Bergström (1976) in his description of the HBV model. However, it was modified to take into account that basin response in large basins with small to gently undulating slopes depends on the antecedent accumulated rainfall amounts, soil moisture storage and channel storage. The resulting function represents the weight of surface runoff according to the following:

a) Distribution on consecutive days is computed through a triangular unit hydrograph. Its base is equal to the base time (*TB* days) and its time to peak to (*TP*) days.
b) A monotonic decreasing function establishes a relationship between antecedent accumulated rainfall and the base time (*TB*) and the time to peak (*TP*).
c) The base time (*TB*) and the time to peak (*TP*) are constant for antecedent accumulated rainfall less than P_0 or higher than P_1, where P_0 and P_1 are model parameters representing amounts of antecedent accumulated rainfall. Their values depend on the season of the year, distinguishing low and high evaporation.

The resulting equations are

For $P \le P_0$

$$TB = TB \tag{6}$$

$$TP = TP_0 \tag{7}$$

For $P_0 \le P \le P_1$

$$TB = TB_0 (P/P_0)^{(\ln(TB_1/TB_0)/\ln(P_1/P_0))} \tag{8}$$

$$TP = TP_0 (P/P_0)^{(\ln(TP_1/TP_0)/\ln(P_1/P_0))} \tag{9}$$

For $P \ge P_1$

$$TB = TB_1 \tag{10}$$

$$TP = TP_1 \tag{11}$$

where P is antecedent accumulated rainfall. TB_0 and TP_0 are the base time and the time to peak for events where rainfall is mainly infiltrated and slowly discharged to the basin outlet. TB_1 and TP_1 are the base time and time to peak corresponding to extreme events which produce significative surface runoff. P_0 and P_1 are the limits distinguishing one type of event from the other.

Calibration and Verification

The length of calibration data is a critical time-scale issue. Hydrologists often use as much data as available for the calibration, after setting aside part of the available data for verification. However, the studies carried out by Sorooshian *et al.* (1983) showed that one year of daily data was sufficient to achieve conceptually realistic estimates for the Sacramento model, which is the base of the Hidro-Urfing model. Only a marginal improvement of model parameters was obtained using longer data sets. Gupta and Sorooshian (1985) also suggest that two to three years of calibration should be sufficient due to the pattern of standard errors of parameter estimates. Nevertheless, a requirement is that the data set represents enough variability of the hydrological processes.

The input data base consisted of daily rainfall records measured between 1 January1975 and 30 June 1989, mean monthly values of potential evapotranspiration and daily streamflow records. Five years between 1 January 1975 and 31 December 1979 were selected for the calibration of the Laguna I basin due to its informativeness. The rainfall series includes three normal years (1975, 1976 and 1978 where mean annual rainfall were 1,180 mm, 1,115 mm and 1,274 mm), a wet year (1977 with 1,811 mm) and a dry year (1979 with 968 mm). The most severe storm observed in the 15-year input data base occurred at the end of July and the beginning of August 1977. Its measured peak flow at the Laguna I streamgauge was 2,726 m^3/s. A similar period of five years not used for the calibration was selected to conduct a verification test. The selected period was 1 January 1984 to 31 December 1988 consisting of three normal years (1985, 1987 and 1988 where mean annual rainfall were 1,327 mm, 1,332 mm and 1,098 mm) and two wet years (1984 and 1986 with 1,644 mm and 1,575 mm).

Physical parameters were obtained from topographic and soil maps. Soil units classified as hydrological group D according to the U.S. Soil Conservation Service were treated as impervious areas due to its high runoff potential.

Initial values of process parameters were selected based on judgement and understanding of the available information about soils and the rainfall-evapotranspiration-runoff relationship observed in this large basin with small to negligible slopes. Afterwards, these initial values were adjusted based on a visual comparison between observed and computed hydrographs. This judgement of the model performance was also supported by two criterions on the model fit: 1) the computation of the R^2 value according to the objective function proposed by Nash and Sutcliffe (1970) and 2) daily computation of the simple hydrological balance expressed as

$$HB(t) = \frac{\sum\limits_{t-365}^{t} P - \sum\limits_{t-365}^{t} Q_c}{\sum\limits_{t-365}^{t} ET} \tag{12}$$

where

$HB(t)$ = the annual hydrological balance computed the t-day

$\sum\limits_{t-365}^{t} P$ = the sum of mean observed daily rainfall occurred during the last 365 days

$\sum\limits_{t-365}^{t} Q_c$ = the model computed daily runoff accumulated during the last 365 days

$\sum\limits_{t-365}^{t} ET$ = the model computed daily evapotranspiration accumulated during the last 365 days

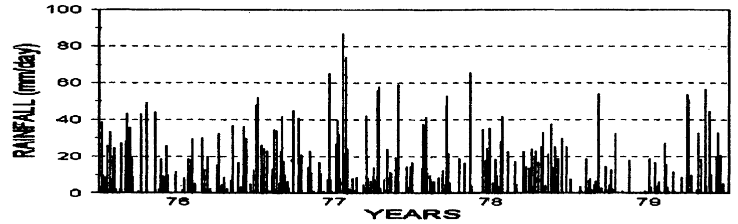

Fig. 3. Computed mean daily rainfall within the Laguna I basin (1976-1979).

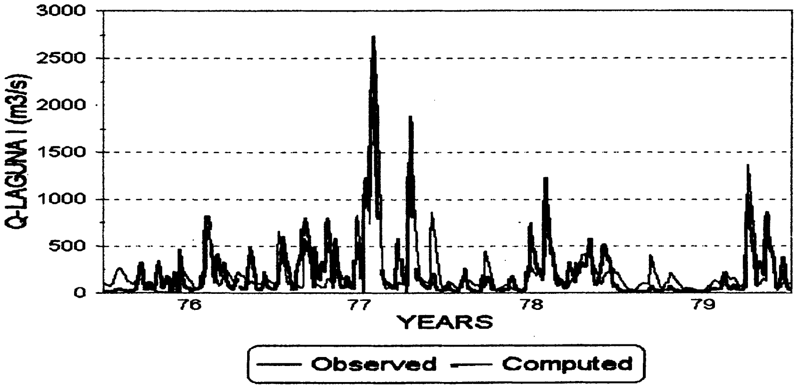

Fig. 4. Calibration: Daily observed and computed runoff.

A daily value of *HB(t)* around 1.0 represents a complete agreement between basin measured inputs (rainfall) and model computed outputs (runoff and evapotranspiration). Values of *HB*(*t*) systematically lower than 1.0 represent water surplus, *i.e.*, $Q_{\text{computed}} > Q_{\text{observed}}$, whereas values of *HB*(*t*) higher than 1.0 represent instead a water deficit, *i.e.*, $Q_{\text{computed}} < Q_{\text{observed}}$.

The first calibration year, 1975, was considered as a period to achieve stability between the arbitrary selected initial physical conditions represented by the state parameters, as soil moisture content of the upper and lower zones, and the physical conditions existing in reality.

Fig. 3 shows computed mean rainfall and Fig. 4 the relationship between observed and computed runoff for the four-year period between 1 January 1976 and 31 December 1979. The R^2 value obtained with the Nash and Sutcliffe objective function is 0.82. Fig. 5 shows that the hydrological balance is normally close to 1.0, ranging between 0.95 and 1.05. Some isolated points range between 0.90 and 0.95.

An analysis of Fig. 4 shows an acceptable agreement between observed and computed streamflow hydrographs for the most severe storm observed in the input data base. Measured peak flow occurred at the Laguna I streamgauge in August 1977 was 2,726 m^3/s and computed peak flow was 2,573 m^3/s. A relative adequate agreement between observed and computed streamflow hydrographs is also observed for the

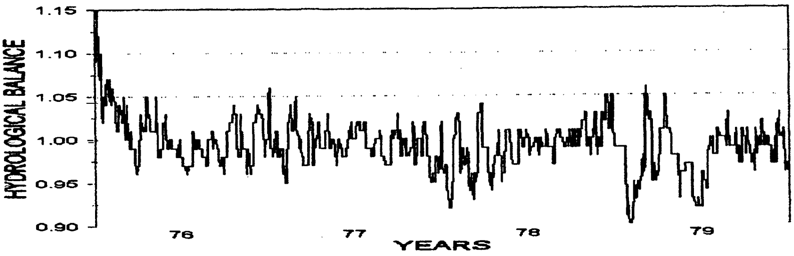

Fig. 5. Calibration: Daily hydrological balance computed for the last 365 days.

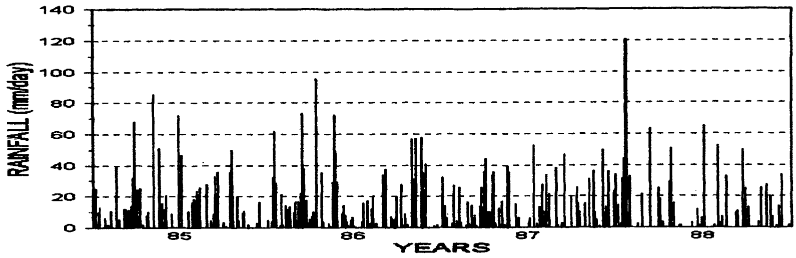

Fig. 6. Computed mean daily rainfall within the Laguna I basin (1985-1988).

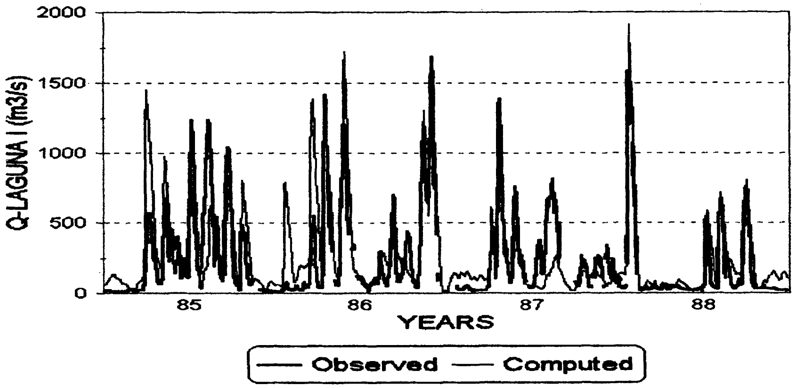

Fig. 7. Verfication: Daily observed and computed runoff.

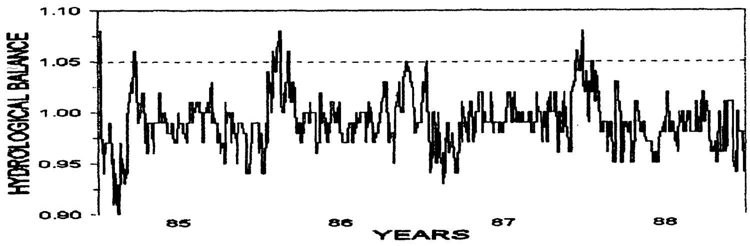

Fig. 8. Verification: Daily hydrological balance computed for the last 365 days.

next severe storm occurring in October 1977.

Storms with observed peak flows larger than 250 m^3/s show an overall agreement between observed and computed hydrographs, whereas storms with observed peak flows lower than 250 m^3/s show some disagreements. An analysis of rainfall input data showed that most of these disagreements are due to local not uniformly distributed storms which are treated by the model as uniformly distributed over the whole basin, in other word a spatial-scale issue.

Fig. 6 shows computed mean rainfall and Fig. 7 the relationship between observed and computed runoff for the verification period between 1 January 1985 and 31 December 1988. The R^2 value is 0.79 and the hydrological balance in Fig. 8 is also close to 1.0. The hydrographs corresponding to the major storms show an adequate agreement between observed and computed runoff.

Discussion and Conclusions

Runoff generation depends on two phases: land and channel phases. In large basins with small slopes in the temperate zone, where the hydraulic conductivity decreases with depth due to an essentially impervious B-horizon, surface runoff generation on the land phase depends strongly on the antecedent soil moisture condition. Two seasons of low and high evapotranspiration were distinguished to characterize the antecedent soil moisture condition which depends essentially on vertical fluxes, in other words the relationship between rainfall and evapotranspiration. This relationship was taken into account by the antecedent accumulated rainfall (P) and the limits (P_0) and (P_1) distinguishing dry, normal and wet soil moisture condition. The channel phase characterized by channel storage and routing was also considered by the basin runoff response function through the limits for the base time (TB) and the time to peak (TP), Eqs. (6) to (11). Calibration showed that the model is very sensitive to the number of days selected to compute the antecedent accumulated rainfall and the limits TB and TP. Calibration and verification show an acceptable agreement regarding the shape of computed and observed hydrographs for the major storms, both regarding the rising limb and the recession limb. The term acceptable refers here to this first step in order to model large basins in temperate zones with a lumped conceptual model in only one step. Hydrographs with peak flows lower than, *e.g.*, 250 m^3/s are poorly represented by the model. This seems to be due to the spatial-scale issue. Local storms close to the basin outlet or far from the basin outlet are examples of rainfalls not uniformly distributed which are treated by the model as uniformly distributed over the whole basin.

Quality of the input data base is also a major constraint regarding calibration and verification of the model. The range of streamflow measurements carried out by the electricity company is still limited (up to 1,400 m^3/s) and thus, the rating curves were extrapolated in order to simulate higher floods. Uncertainty between extreme flows occurred in reality and observed streamflows computed according to the existing rating curves is difficult to quantify. Usually, normally controlled river sections are unable to transport as much water as for example the extreme peak flow of 2,726 m^3/s observed in the Laguna I basin during 1977. Extreme storms usually produce extensive floodplains due to the flat topography. An improvement of the existing rating curves is therefore possible but also limited. Much attention was also paid to analyze the quality of the existing rainfall data and to work out a data base. Nevertheless, the input data base may still contain errors that affect the computation of a daily average rainfall estimate according to the Thiessen method and consequently also the resulting computed streamflow.

While the results of the Hidro-Urfing model presented in the paper have provided valuable insights into the runoff response of large basins with small slopes in the temperate zone, it is not ready to be used in a practical context to simulate low flows. Rainfall inhomogeneities suggest that further research should also investigate the optimal subdivision into smaller sub-basins in order to improve the accuracy of the model but also to reduce the number of necessary streamgauges. Other spatial-scale problems may be due to estimation of evapotranspiration and soil data parameterization. Quality of the input data base requires also further research.

The focus of most research performed on small basins, *i.e.*, less than 1 km^2 and up to 10 km^2, is on the identification of saturated areas near related to generation of surface runoff. Instead, this research intended a broader view in order to examine the runoff response of large basins, *i.e.*, larger than 10,000 km^2, with small slopes in the temperate zone. The final purpose should be to improve the use of natural water resources of flat areas by optimizing the spatial-scale issue and also the number of measurements points.

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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