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MONTHLY RUNOFF GENERATION BY NON-LINEAR MODEL USING MULTISPECTRAL AND MULTITEMPORAL SATELLITE IMAGERY

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ABSTRACT

A monthly cloud cover index (CCI) is determined as a function of the threshold cloud top temperature(IR channel), the "reflectivity" of the cloud(VIS channel) and the state of the environmental mean relative humidity in the upper troposphere (WV channel) using multispectral and multitemporal satellite imagery and is transformed into monthly area precipitation. Consequently the rainfall based on satellite information is transformed into monthly runoff values with the aid of the non-linear Volterra series model. The approach is tested in West Africa, in the Tano river basin in Ghana, which cover an area of about 16.000 sq. km.

INTRODUCTION

Often the design of water management systems in the developing countries suffers from very short time series of hydrological data. It is well appreciated that a runoff series which goes far enough back to include typical long-term variations is a prerequisite for the successful planning and design of reservoirs for hydropower, water supply, irrigation and other water use systems. Although statistical methods enable the designer to generate synthetic data, the success of these methods also depends on the length of the available data series from which the statistical model parameters are derived. Unfortunately only very few rivers in the developing countries have runoff records which satisfy the above requirements. Consequently it is very difficult to evaluate the reliability with which the water resources project can fullfill its purpose.

The idea of the research project presented in this paper can be described as follows: At the beginning of the design of a water resources project-if no hydrological data are available- a hydrological network will be installed which will collect data (ground truth) during the planning period of usually one to three years. On the basis of these data a mathematical model can be developed which connects the ground truths to data obtained from satellite imagery. After calibration and validation of the mathematical model it becomes possible to reconstruct historical river flows with the aid of the mathematical model on the basis of satellite data alone for the period of time for which satellite information is available. This way, the very short time series of hydrological data can be extended considerably thus allowing an estimate of the future performance of the water project in terms of reliability indices.

STUDY AREA AND DATA USED

Due to the fact that the mathematical hydrological model discussed here is mainly meant for planning water management systems in developing countries, it seemed adequate to choose a test area in the tropics. On the basis of an existing cooperation between the Institute of Hydrology, Water Management and Environmental Engineering of the Ruhr-University Bochum and the Water Resources Research Unit, CSIR, in Ghana, West Africa, it seemed suitable to choose the Tano river basin in Ghana comprising a catchment area of about 16 000 sq. km.

In the Tano basin daily records from 23 raingauges for the period from 1983 to 1984 are available. The raingauge density is 1 gauge per 700 sq. km and their distribution over the catchment is reasonably uniform. Additionally measured monthly runoff values and monthly rainfall for the periods from 1969-1972, 1975-1976 and 07/1984-04/1985 are also available. The observed daily rainfall data are accumulated into monthly values since for planning purposes of water management systems monthly runoff values are used. The required monthly area precipitation is computed from point measurements with the aid of the reciprocal distance weighting method (Solomon et al. 1968).

Since there is a trade-off between required model accuracy and amount and costs of the data aquisition and processing, a compromise was made in the model presented here. The so called B2 Meteosat data were used which contain only every sixth pixel in a line and every sixth line in all three Meteosat spectral channels (VIS: 0.4-1.1 μm; IR: 10.5-12.5 μm; Water Vapour (WV): 5.1-7.1 μm). The time resolution was chosen to be 3 hours.

ASSESSMENT OF MONTHLY AREA PRECIPITATION ON THE BASIS OF MULTISPECTRAL AND MULTITEMPORAL SATELLITE IMAGERY

A number of scientists have already used data from geostationary satellites to compute precipitation (e.g. Arkin 1979; Griffith 1978). Many of their schemes are, however, based on the individual tracking of clouds entities throughout their lifetimes. These methods require substantial computing capacity and are applicable only over limited areas in space and time periods. For the reconstruction of long hydrometeorological time series the method for deriving rainfall estimates has to be relatively simple. Arkin (1979) has shown that the fractional cloud cover colder than a certain cloud top threshold temperature is proportional to the accumulated rainfall amount. This approach constitutes a feasible solution for the research project presented here.

There are, however, some limitations in the Arkin scheme. The threshold cloud top temperature is the only parameter taken into account, although two clouds with the same cloud top temperature and with comparable sizes produce different rainfall amounts depending on the state of their environmental humidity (Krüger and Schultz, 1982). Clouds in a moist environment produce considerably more rain than those in a dry environment. The influence of the humidity on the rainfall activity is also emphasized by Adler and Mack (1984). Poc et al. (1983) and Schmetz et al. (1988) found a relationship between the radiance of the WV channel of the Meteosat satellite system and the mean relative humidity in the upper troposphere. The mean relative humidity in the upper troposphere obtained from the WV channel can be used as an indicator for the humidity state of the environment of clouds or clouds systems(Papadakis and Schultz, 1990).

Furthermore high and thin ice cirrus clouds with very low cloud top temperature certainly produce no rain. The brightness characteristics in the VIS channel and temperature characteristics in the IR channel allow the distinction between non-precipitating cirrus clouds and those with rainfall activity.

ESTIMATION OF THE MONTHLY CLOUD COVER INDEX (CCI)

In order to overcome the above mentioned limitations of the Arkin method, a monthly cloud cover index (CCI) is estimated as a function of a certain cloud top threshold temperature, certain threshold "reflectivity" of the cloud and the state of the environmental mean realtive humidity in the neigbourhood of the cloud. Consequently the CCI is transformed into monthly rainfall values. The determination of the CCI consists of four consecutive steps, namely:

Step 1: Registration of the cloud cells colder than a certain threshold cloud top temperature covering the catchment area under consideration either totally or partially in the IR channel. Three-hourly time intervals are chosen.

Step 2: Addition of all pixels for every cloud cells as obtained in step 1 within the catchment area under consideration.

Step 3: Registration of the "reflectivity" (R) for every cloud cell within the catchment area as registred in step 1 on the basis of data in the VIS channel. This can be done, however, only for those time interval for which visible information is available(during day time).

Step 4: Estimation of the mean relative humidity (H) in the environment of a cloud cell as obtained in step 1 within the upper troposphere on the basis of data from the WV channel.

The result of this procedure consists of three-hourly cloud cover indices having values between 0 and 1 representing the relative area of the total river basin under consideration for which a certain information, relevant for precipitation, is obtained in one or more Meteosat channels. The relative area is expressed by the number of relevant pixels divided by the total number of pixels within the catchment area.

The CCI which is of interest for the hydrological computations is simply the sum of the three-hourly indices for the whole month.

THE RELATIONSHIP BETWEEN CCI AND MONTHLY AREA PRECIPITATION

To estimate the monthly precipitation, the empirical relationship of best fit is determined using the least-squares method. Different parameters depending upon the radiance, e.g the threshold cloud top temperature (from the IR channel), the "reflectivity" (from the VIS channel) and the state of the environmental mean relative humidity in the upper troposphere (from the WV channel) were varied in order to obtain an optimum agreement between observed monthly rainfall and spectral information from Meteosat. Since the rainfall activity in west Africa is dependent in space and time from the migration of the ITDZ(Intertropical Discontinuity Zone) two well defined seasons are considered(Ojo,1977).

The empirical relationships of best fit which are obtained are as follow:

i) The monthly area precipitation (P) and the CCI obtained from the three spectral channels with values of $T \leq -20^{\circ}C$ and $R \geq 80$ digital counts for the IR and VIS channel respectively and three mean relative humidity intervals of $0<H_1\leq 30\%$, $30<H_2\leq 80\%$ and $H_3>80\%$ for the WV channel(Fig. 1)

Season1: Apr., May, June, Sept.

$$P = 0.3 * 10^{-2} CCI^{0.003}_{(T,R,H_1)} + 109.9 CCI^{0.17}_{(T,R,H_2)} + 0.4 * 10^{-3} CCI^{0.02}_{(T,R,H_3)} \quad (1)$$

Season2: Jan., Feb., March., July, Aug., Oct., Nov., Dec.

$$P = 0.7 * 10^{-5} CCI^{1.7}_{(T,R,H_1)} + 2.8 CCI^{1.2}_{(T,R,H_2)} + 9.4 CCI^{0.8}_{(T,R,H_3)} \quad (2)$$

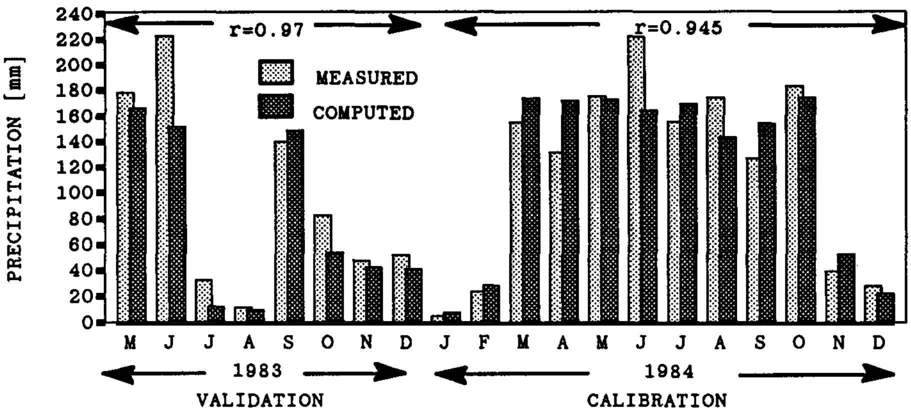

Fig. 1. Comparison between observed and computed monthly rainfall on the basis of three spectral channels (IR, VIS, WV).

ii) The monthly area precipitation(P) and the CCI obtained from two spectral channels (IR, VIS) with values $T\leq -20°C$ and $R\geq 80$ digital counts for the IR and VIS respectively(Fig. 2):

Season1 $P = 85.3 CCI^{0.2}_{(T,R)}$ Season2 $P = 4.4 CCI^{1.02}_{(T,R)}$ (3,4)

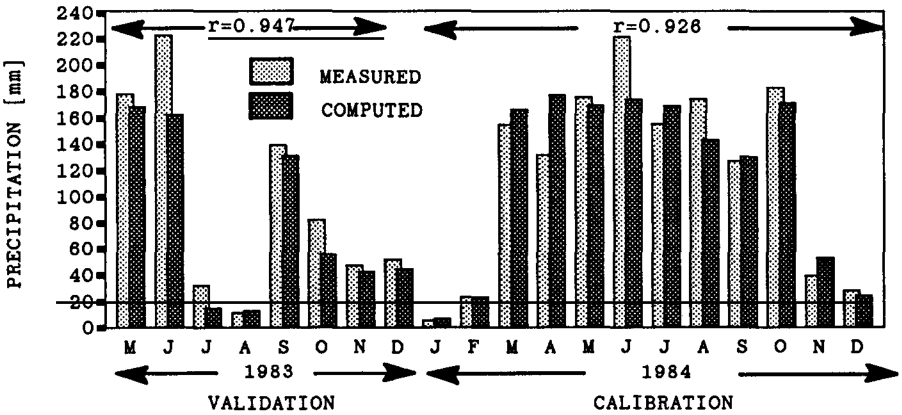

Fig. 2. Comparison between observed and computed monthly rainfall on the basis of two spectral channels (IR, VIS).

iii) The monthly area precipitation(P) and the CCI obtained from two spectral channels (IR, WV) with values for the IR channel and mean relative humidity intervals as by (i) (Fig.3):

Season1

$$P = 0.2 * 10^{-4} CCI^{0.024}_{(T,H_1)} + 105.1 CCI^{0.17}_{(T,H_2)} + 0.23 * 10^{-2} CCI^{0.008}_{(T,H_3)} \quad (5)$$

Season2

$$P = 0.3 * 10^{-6} CCI^{0.69}_{(T,H_1)} + 2.3 CCI^{1.2}_{(T,H_2)} + 3.6 CCI^{1.06}_{(T,H_3)} \quad (6)$$

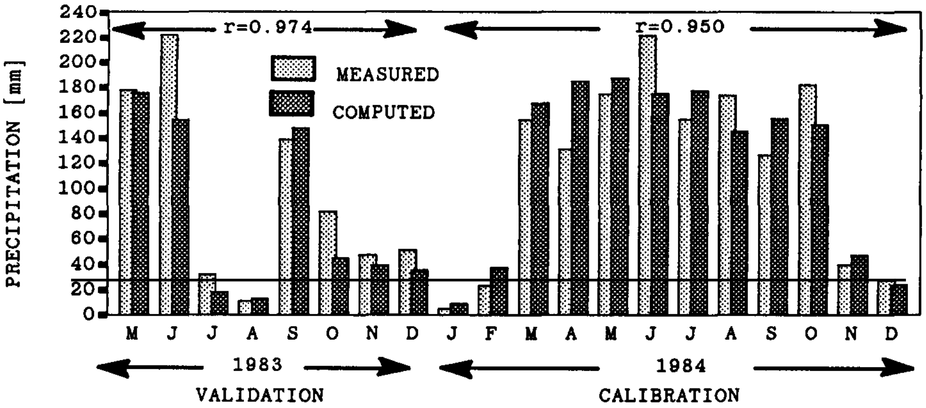

Fig. 3. Comparison between observed and computed monthly rainfall on the basis of two spectral channels (IR, WV).

iv) The monthly area precipitation(P) and the CCI obtained from one spectral channel(IR) with values for the IR channel as by (i)(Fig. 4):

Season1 $P = 101.4CCI_{(T)}^{0.13}$ Season2 $P = 2.03CCI_{(T)}^{1.2}$ (7,8)

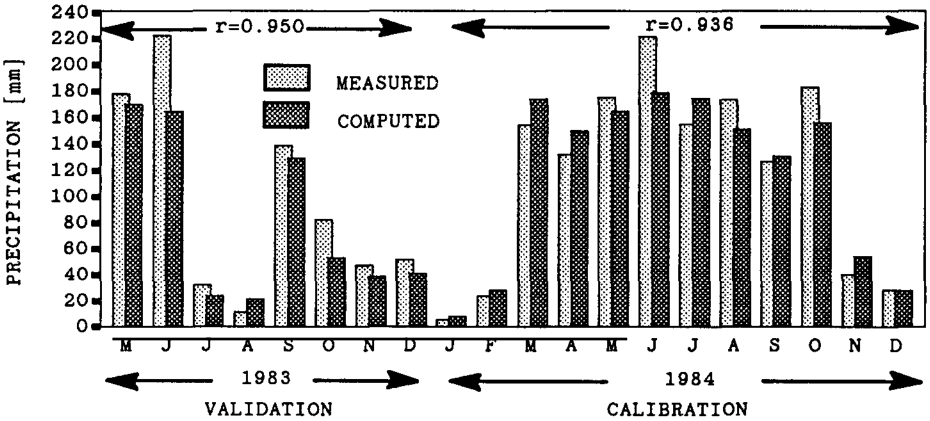

Fig. 4. Comparison between observed and computed monthly rainfall on the basis of one spectral channel (IR).

RAINFALL-RUNOFF MODEL

In the case of surface runoff from the TANO catchment, an accurate application of the hydraulic approach would require a detailed topographical and geological survey and determination of roughness parameters. In order to avoid these difficulties, the method applied in this paper combines black box analysis with the conceptual model approach. To describe the non-linear behavior of the catchment the rainfal excess is obtained and then tranform into direct runoff by means of a model in the form of a second-order approximation of a cascade of non-linear reservoirs. Such a model is equivalent to the first two terms of a Volterra series (Napiorkowski, 1986):

$$y(t) = \int_0^t h_1(\tau)x(t-\tau)d\tau + \int_0^t\int_0^t h_2(\tau,\sigma)x(t-\tau)x(t-\sigma)d\tau d\sigma \tag{9}$$

where: x is the rainfall excess(Input) and y is the direct runoff (Output).

For that model, which combines linear static and non-linear dynamic characteristics, the structure of the kernels was shown to be (Napiorkowski and Strupczewski, 1979):

$$h_1(\tau) = aH_n(\tau) \tag{10}$$

$$h_2(\tau,\sigma) = b\left(H_n(\tau)\sum_{i=1}^{n} H_i(\sigma) + H_n(\sigma)\sum_{i=1}^{n} H_i(\tau) - H_n[\max(\tau,\sigma)]\right) \tag{11}$$

where: $$H_i(\tau) = \exp(-a\tau)(a\tau)^{i-1}/(i-1)! \tag{12}$$

The two equations for the kernels are linked through the fact that an auxiliary function $H_n(\ )$ and two parameters, reservoir time constant (α) and the number of reservoirs (n), appear in the equations of both kernels.One can see that $h_1(\ )$ given by eq. 10 is the well known transfer function for a cascade of linear reservoirs. Note that the second order kernel described by eq. 11 affects only the distribution of the predicted runoff ordinates and the total value of the second component is zero.

The significant advantage of the conceptual Volterra model is parsimony in the number of parameters, ensuring that the identification problem is well posed. Moreover, the problem of identification can be reduced to optimization with respect to two variables integer (n) and positive (α) only. For given (n) and (α), the parameter (b) results from the necessary condition for optimum.

PARAMETER IDENTIFICATION

The objective is to solve the problem of identifying the three parameters n, α and b of the model for the watershed under consideration. The data of rainfall and corresponding runoff observed from 1969-1972 are used. It was found that due to the evaporation the effective rainfall is 16% and 20% for the wet and the dry season respectively. The optimal values of the parameters and the degree of the fit to measured data are shown in Fig. 5.

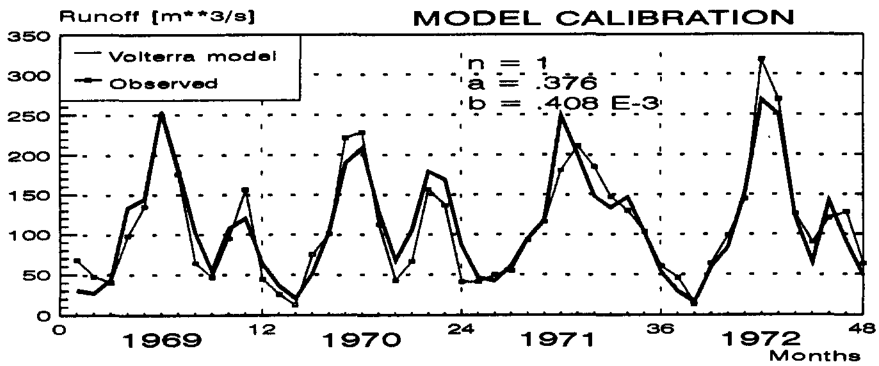

Fig. 5. Model calibration. Comparison between observed and estimated monthy runoff values.

The model thus obtained was tested by using the data of the years 1975-1976. The resulting fit is shown in Fig. 6 and can be cosidered to be adequate.

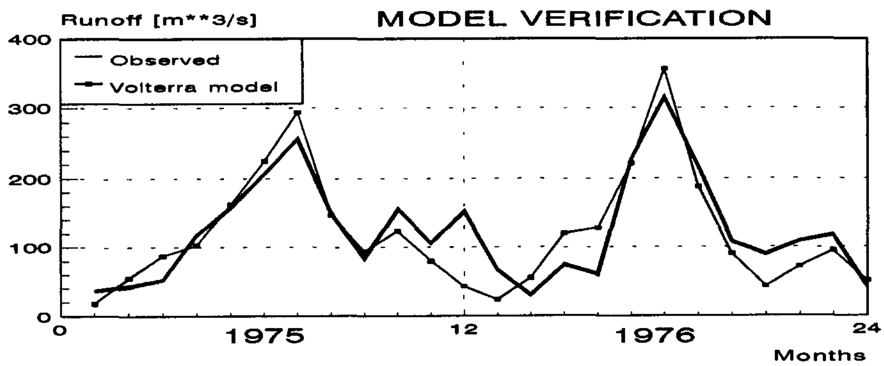

Fig. 6. Model Verification. Comparison between observed and estimated monthy runoff values.

Consequently, the rainfall based on satellite information is transformed into monthly runoff for the period when both satellite data and runoff were available, namely from 07.1984 until 04.1985. The resulting fit is shown in Fig.7 and is found to be satisfactory.

RESULTS AND CONCLUSIONS

It was the aim of the study to find out how well a historic time series of monthly runoff in a river basin can be reconstructed on the basis of satellite data alone with

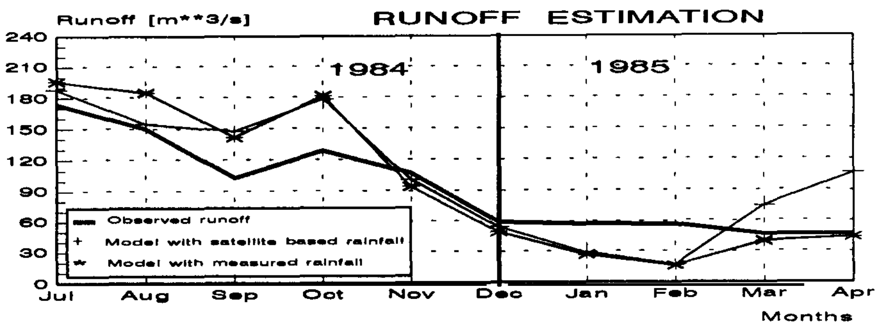

Fig. 7. Comparison between observed and estimated runoff values on the basis of satellite data.

the aid of a non-linear rainfall-runoff model. The remote sensing data base for this study was a time series of Meteosat data. From the study the following conclusions can be drawn:

-The relationship between monthly rainfall and monthly cloud cover index obtained from satellite spectral information is non-linear.

-From the three spectral channels which were used in the analysis (VIS, IR, WV) the IR data are the most important in this case . The addition of information from the VIS channel to IR data renders no improvement due to the fact (after further analysis) that the rainfall activity in the area under consideration dominates in the night time where no VIS information is available. The addition of WV data to IR data shows a slight improvement (r=0.95 as compared to r=0.93). The use of all three spectral channels (IR, VIS and WV) renders no improvement.

-When the water vapour channel is used, it can be seen from the equations 1,2, 5 and 6 that the contribution of the low humidity values 0-30% is zero. Also the contribution of the humidity higher than 80% is mostly rather small probably due to frequent cloud contamination by cold non-precipitating cirrus clouds.

Although in the analysis only Meteosat B2 data were used (only each sixth pixel in a line from each sixth line) it can be concluded that the satellite-based monthly precipitation, when transformed by the non-linear Volterra series model, generates monthly runoff values that are accurate enough for hydrological purposes. However for the complete evaluation of the presented technique a longer verification period is required.

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