Hydrologic Applications of Space Technology (Proceedings of the Cocoa Beach Workshop, Florida, August 1985). IAHS Publ. no. 160, 1986.

Water levels of a sahelian lake (Mare d'Oursi — Burkina Faso)

P. CHEVALLIER
Centre Orstom, B.P. V51, Abidjan, Ivory Coast
M. LOINTIER
Centre Orstom, B.P. 165, 97323 Cayenne, French Guyana
B. LORTIC
Centre Orstom, 70, rte d'Aulnay, 93140 Bondy, France

Orstom: *Institut Français de Recherche Scientifique pour le Développement en Coopération*

Abstract

The authors present a modelisation of the water levels as daily computed of the "Mare d'Oursi", a sahelian lake (Burkina Faso), on the basis of a "space-gridded model". This deterministic model uses a grid to divide the catchment into several squares. A mean production (rainfall and runoff) function is alloted to each squares. A certain number of natural or artificial pools may be introduced and taken into consideration for the transfer function to the catchment outlet.

Two original methods have been brought into the model elaborated and fitted to the specific conditions of the "Mare d'Oursi":

(1) Runoff simulation : The characteristics of the production function are deduced directly from measures of runoff and rainfall on experimental plots using a rainfall simulator.

(2) Remote sensing : The surface features of the soils are the main factors of the rainfall-runoff function. A map of these surface features for the whole catchment is drawn from a multispectral classification of LANDSAT data. Thus, the physiographical characteristics of each square are automatically deduced from this numerical representation.

This method has been tested three years running through field observations. Extremely dry and humid conditions, as well as a mean condition were simulated.

Introduction

Classical hydro-pluviometric observations have been carried out during six years (1976-1981) on the representative watershed of "Mare d'Oursi". The use of rainfall simulation on the watershed of Polaka (9,14 km2) and Jalafanka (0,80 km2) enabled us to draw up a first attempt at reproduce flooding from the results obtained from the representative plots of the morpho-structural units (Valentin, 1981 ; Chevallier, 1982).

It seemed interesting to employ two other recent tools of hydrology in combination with rainfall simulation :

(1) remote sensing for the mapping of the morphostructural units.

(2) the Orstom-Ecole de Mines's space gridded model the determinism of which is particularly well adapted.

It seems unnecessary to detail the site and the environment of the "Mare d'Oursi"'s basins which have been fully described by Chevallier and al. (1985), except to mention that the study is located in the north of Burkina Faso in the heart of the Sahelian climatic zone. The average annual rainfall is about 400 mm. The varied landscapes are representative of the region known as the "Boucle du Niger".

Rainfall Simulation and Space Gridded Modeling

Space gridded modeling has been improved since 1972 by Girard (ORSTOM) with, at first, collaboration of scientists of Institut National de la Recherche Scientifique du Québec (INRS-Eau) (Girard, Morin, Charbonneau, 1972). Later, the E.N.S.M. of Paris hydrologists worked with them, introducing underground component.

The first step of space gridding is the representation of the watershed by squares. The size of the squares being adapted to the basin physiology and morphology.

On this set of representative squares of the hydrological system, we define five interconnected functions wich modelise the water cycle :

(1) input function representing contributions to the system (mainly rainfall, occasionally external contribution from surface or underground flows).

(2) *production function (for each kind of soil)* defining the hydro-assessment, i.e. the distribution of inputs between evaporation, runoff and infiltration (superficial and underground storage).

(3) surface transfer function defining the surface water transit conditions, from one square to another.

(4) underground transfer function defining underground water transit conditions.

(5) surface/underground crossing function giving mutual exchange conditions.

These five functions must be perfectly defined in space and time (choice of period of calculation compatible with the problem to be solved).

The production function is the essential element in modeling. Each surface feature unit determines its own function. Several production functions may be found in a single square. They contribute proportionally to the surface occupied by each feature unit on the square.

To study the "Mare d'Oursi", it seemed interesting to employ a production function obtained directly from the results on the experimental plots with a rainfall simulator (Chevallier, 1982). Priority is given to runoff since, for a given plot, the simulator produces a depth of flow depending of the height and the antecedent precipitation index (API).

A characteristic equation for an experimental plot can be drawn up from rainfall simulation, and consequently for a unit of surface (an experimental plot represents one unit or "theme").

The equation can be writen :

$$QR = AA * P + AB * API1 + AC * P * API1 - AD$$

where QR is the depth of flow,

AA, AB, AC, AD are constant characteristics,

P the height of rainfall,

API1 the value of the antecedeant precipitaion index at the onset of the shower which produce runoff.

Girard and Rodier (1979) suggest an equivalent calculation for short periods of time with a slightly different characteristic equation.

Two versions of the space-gridded model have been used for the

"Mare d'Oursi" :
(1) A "coupled" model (Girard, Ledoux, Villeneuve, 1981) was developed jointly by the "Laboratoire d'Hydrologie de l'Orstom" and the "Centre d'Informatique Géologique de l'Ecole des Mines de Paris". It uses the fives interconnected base functions to model the water cycle. In the Mare d'Oursi case , this model was used for the simulation of flood of the Polaka basin. The recorded outflows are entirely due to runoff and only the production function and transfer function have been used. The selected period of calculation was 36 mins (1/40th day) corresponding to the relatively short periods of flooding which last 3-5 hours without increasing the number of iterations in order to keep costs low.
(2) The main inconvenience of the "coupled" model is that it doesn't take into account hydraulic development of the surface area or of natural changes. The MODLAC model was design to counterbalance this and to help in the planning of the rational management of surface water (Girard, 1982). This space-gridded model simulates the flows on a hydrological system made up of a set of basins. Each basin may include a certain number of natural or artificial reservoirs. It was selected to simulate the filling of Mare d'Oursi, taking into account the vast flood plains which are comparable to reservoirs.

Landscape Mapping and Satellite Remote Sensing

LOTERIE Procedure Used for Surface Feature Mapping (Lointier and Lortic, 1984).--In space-gridded model, production functions are defined for a surface unit which presumed to have a homogeneous surface. The production function is a linear combination of production functions for each of the surface units present in one square, obtained in proportion of the types of surfaces).It is therefore necessary to draw up an accurate, exhaustive map of the studied area.

To study the origin of floods with the help of a rainfall simulator, (Chevallier, 1982) and Valentin (1981) a map of the morpho-structural differentiations of the Polaka watershed was required. This approach has been repeated since in other basins in Burkina Faso, Ivory Coast, Congo, Niger and Togo.

This map (fig. 1) shows 11 units and directly fits for the keying space gridded models. However, this method is only possible for small areas such as the Polaka watershed (9,14 km2) and requires an experienced pedologist and as surface areas increase, the problem quickly becomes insoluble.

Satellite remote sensing is therefore an ideal new technique for the constitution of landuse data base (Lointier and Pieyns, 1981). The Sahel with its ground easily visible by satellite, clearly defined landscapes, sparse vegetation and few human settlement appears as a particularly interesting region for such studies.

The mapping of morpho-structural differentiations of the Polaka basin provides an excellent "ground truth" for the keying of MSS data obtained from satellites.

For the "Mare d'Oursi" region there are many views (covering a surface of 180 x 180 km centred on a point just West of the town Dori) taken by the scanners of the American satellites Landsat.

The image selected for analysis is that of 4th feb. 76. The 4 bands of the MSS are available.

By image processing, two new band are available (7-5 and 7+5) made up from the original bands 5 and 7. The neo-band 7-5 gives the state of the vegetation (but not only that) and 7+5 gives the surface brightness, relief and hydrographic network (Lortic, 1982).

A "multivariate" analysis using these two new bands with the LOTERIE procedure (Lointier and Pieyns, 1981) enabled us to determine a certain number of "lots" by using the "ground truth" map and knowledge of the environment. These 48 lots can be classified under 9 headings :
(1) Shifting sands, e.g. the Oursi dune.
(2) Rocks (gabbros, green rocks and hardpans).
(3) Hardpans debris.
(4) Fragments of various rocks.
(5) Gravels.
(6) Granitic and coarse sands.
(7) Surface crust.
(8) Fine sand, dune bar.
(9) Vegetation.

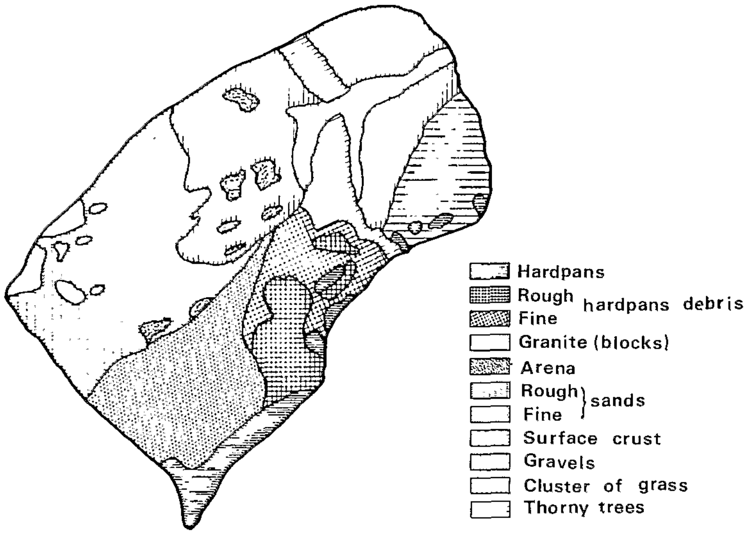

FIG.1 Morpho-structural differentiations of Polaka watershed.

The map of these 9 ground surface types for the Polaka watershed can be compared with that drawn up on the ground by Valentin (1981). It demonstrates that the extension of this "ground truth" method to the whole of Mare d'Oursi basin may be used with very little error.

For easy reading, class # 9 was artificially divided into a class # 9 (vegetation and low ground) and a class # 10 (areas of free water, covered or not by aquatic vegetation) from previous knowledge of the natural environment.

This image processing was done directly on screen of the specialize computer Pericolor 1000 which has a certain number of preprogrammed functions for image analysis. The LOTERIE procedure is automatically used from parameter introduced by the operator.

Automatic Space Gridding.--The following processing is linked to the technical possibilities of P 1000 and we are interested mainly in the final results. The ground survey satellites Landsat give images made up of parallelograms (pixel) 56x79 m (approx. 0,45.10-2 km2). The result of the LOTERIE classification is to give each pixel a class number wich can be materialized on the screen by a colour. One characteristic of Pericolor is to visualize a square pixel. The image (256x256 pixels) is geographically false : a square on the ground becomes a parallelogram on the screen lying on an axis WSW/ENE. In order to represent the whole watershed of the "Mare d'Oursi" it is necessary to divide it into two parts (east and west), each part covering a surface of 14,3x20,2 km. Markers can be used on the Pericolor to define various limits. These markers are used to draw the basic squares of the space gridded model. The main difficulty is the necessary correction of the geographical distortion. The drawing of straight lines is carried out automatically by a program. The result of east half of the "Mare d'Oursi" watershed is shown in fig. 2.

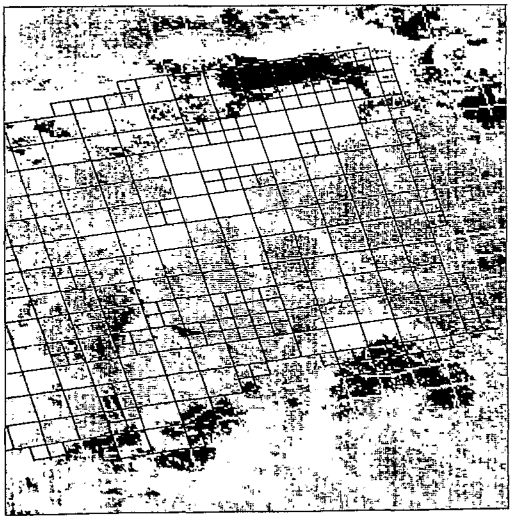

FIG.2 East part of the "Mare d'Oursi" watershed; copy of the Pericolor screen.

A manual slide is used to pick out each square and to obtain instantaneously the percentage of the 10 classes comprised in each. These results can be transferred as they are to the routine GEOCOU. This program characterizes the average production function of a given square by composing.

For example the following table gives the characteristics of a few squares selected from the "Mare d'Oursi".

Table 1 : Correspondence of selected squares :

number of square	percentage for each lot 1	2	3	4	5	6	7	8	9
14	97							3	
95									100
208				5		38	40		17
234					43	38	8	10	
345			1	47			47		5
405		82	11						7

Square # 14 represents the Oursi dune ;
95 the lake of Oursi ;
208 the flat open country of Taïma ;
234 the middle of Taïma watershed ;
345 the lower part of Tchalol watershed ;
405 the hillock of Kolel.

Results

The Model Adjustment.--The space-gridded model is adjusted mainly from the parameter of the production function , but it is difficult to achieve. Although the production function is quite representative of the hydrodynamics of the soil unit, the response curve of the model must be adequate.

As far as the "Mare d'Oursi" is concerned, the production functions are entirely defined by the results of the rainfall simulation which are used without any modification (Chevallier, 1982). The observations made from the study of the Polaka watershed are applied to the whole watershed of the "Mare d'Oursi".

Comparison Between the Levels Observed and the Modelized Levels in the "Mare d'Oursi".--The production functions of the space-gridded model were not subjected to any basic modification from the Polaka watershed (9,14 km2) to the "Mare d'Oursi" watershed (263 km2). It is easy to shift from the coupled model to the model with reservoirs since the production functions are evaluated in a similar way.

The model was tested in order to evaluate the water levels of the "Mare d'Oursi" in 1978, 1979 and 1980 using an initial readings of 2,88 m on January 1st, 1978 (it must be added that the drying level is close to 1,00 m).

Figure 3 shows the comparative results of the observed and modelized levels of the "Mare d'Oursi". The time interval used to make evaluations is the days, but in order to make the interpretation easier, the readings considered are those corresponding to the first day of each month.

One can note that the model is quite adequate, except maybe for the maximum value observed in 1978 along with its consequences on the following low value. This difference can be accounted for only by the monthly evapotranspiration the mean value of which remained unchanged over the three years. The latter ranges from 7 to 10 mm/day and owing to a drier and more windy climate, it can be subjected to variations which can be notable, when cumulated.

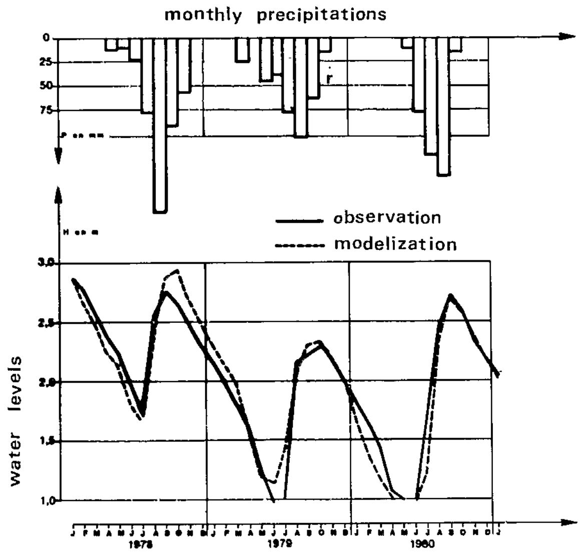

FIG.3 Observed and modeled levels of the "Mare d'Oursi".

Simulation of Levels in the "Mare d'Oursi" under Different Extreme and Mean Rainfall Conditions.--It is interesting to use modelization in order to simulate the variations of the levels of the "Mare d'Oursi" under specific conditions. Three fictitious rainfall events were selected from the Gorom Gorom raingauge station. It is a question of repeating three times the same annual rainfall sequence and of observing the evolution of the water levels in the "Mare d'Oursi".

(1) First hypothesis (extremely humid) : the year 1958 is repeated three times and the total rainfall amount to 691 mm, which corresponds to a humid 50-years return period.

(2) Second hypothesis (mean) : the year 1967 is repeated three times and the total rainfall amount to 465 mm and are roughly equal to the interannual mean.

(3) Third hypothesis (extremely dry) : the year 1971 is repeated three times and the total rainfall amount to 200 mm, which corresponds to a dry 100-year return period.

The simulation was applied in the three hypotheses on the basis of the rather low reading of 2,88 m (corresponding to January 1st, 1978).

Figure 4 shows the results obtained and leads to the following conclusions :

(1) First hypothesis.-- The general level of the "Mare" increases regularly up to 6,00 m and above it, wich is considered as the overflowing level (levelling amounts to 6,33 m, but such amounts of rainfall are likely to lead to erosion at the potential outlet). Therefore, it is possible that the "Mare d'Oursi" overflow over the last years.

(2) Second hypothesis.-- The levels of the "Mare d'Oursi" tend to reach an equibrium ranging from 2,50 m to 4,30 m, wich would make the illusion during the periods of mean or balanced rainfall and urge the people to believe that the "Mare" was perennial, thus leading them to use it. A return to sucessions of rainfall closer to the interannual mean would allow the "Mare d'Oursi" to recover its equilibrium.

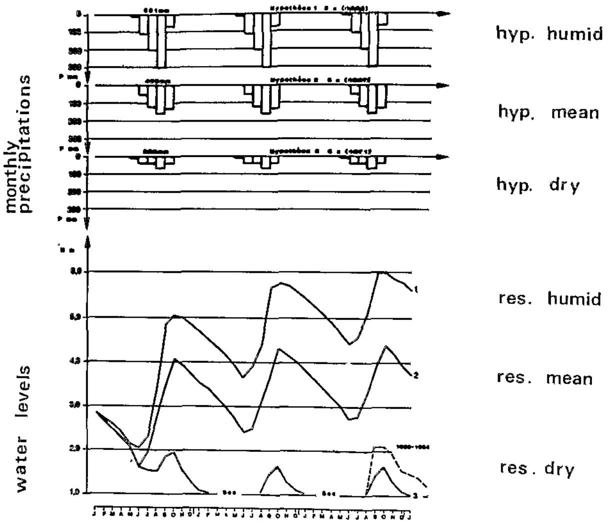

FIG.4 Simulation of levels in the "Mare d'Oursi".

(3) Third hypothesis. -- The figure speaks for itself. The "Mare" is drying up from February to July, such was the case over the last years. It can be observed that the variations recorded in the 1983-1984 year (maximum level amounting to 2,17 m in August and drying up in early March) are hardly better than those recorded for the extreme simulation.

Conclusion

Therefore, one can realize that the comparison of these new methods of research in surface hydrology, namely the rainfall simulation and the satellite remote sensing with a rather efficient determinist model gives quite satisfactory results in the Sahelian zone where the green cover exerts a small influence.

It is encouraging, but there are still some difficulties in applying this type of approach to much more complex environments such as the forest or the dense savannah where vegetation tends to prevail over the soil surface.

As part of the Hyperbav Project carried out in the Ivory Coast since 1983, in a humid savannah zone, one plans to test again the method by using the SPOT satellite data if they are of good quality.

References

Chevallier, P., 1982, Simulation de pluie sur deux bassins versants sahéliens (Mare d'Oursi - Burkina Faso): Cah. Orstom, sér. Hydrol., vol. XIX, n°4.

Chevallier, P., Claude, J., Pouyaud, B., Bernard, A., 1985, Pluies et crues au Sahel. Hydrologie de la Mare d'Oursi. Burkina Faso. (1976-1981).: Travaux et Documents de l'Orstom n°190, Paris.

Girard, G., 1975, Application du modèle à discrétisation spatiale au bassin de l'Oued Ghorfa (Mauritanie).: Cah. Orstom, sér. Hydrol., vol. XII, n°3.

Girard, G., 1982, Modélisation des écoulements de surface sur des bassins hydrologiques équipés de réservoirs. Modèle MODLAC.: Cah. Orstom, sér. Hydrol., vol. XIX, n°2.

Girard, G., Ledoux, E., Villeneuve, J.P., 1981, Le modèle couplé. Simulation conjointe des écoulements de surface et des écoulements souterrains dans un système hydrologique.: Cah. Orstom, sér. Hydrol., vol. XVIII, n°4.

Girard, G., Morin, G., Charbonneau, R., 1972, Modèle précipitation-débit à discrétisation spatiale.: Cah. Orstom, sér. Hydrol., vol. IX, n°4.

Girard, G., Rodier, J.A., 1979, Application de modèles mathématiques déterministes à l'étude des crues et de l'écoulement annuel en zone sahélienne.: Proceedings of the Canberra Symposium, dec. 1979, IAHS/AISH Publication n°128.

Lointier, M., Lortic, B., 1984, Mare d'Oursi. Traitement numérique de la vue Landsat du 4 février 1976.: Orstom, Cayenne.

Lointier , M., Pieyns, S., 1981, Télédétection n°4. Méthodologie de constitution d'une base de données d'occupation du sol par télédétection.: Orstom, Initiation et documents techniques n°47, Paris.

Lortic, B., 1982, Création de nouveau canaux par méthode photographiques.: Actes du Symposium International de la Commission VII de la SIPT, Toulouse, sept. 1982.

Valentin, C., 1981, Esquisse au 1/25 000 des différenciations morpho-structurales de la surface des sols d'un petit bassin versant sahélien (Polaka - Oursi, Nord Haute-Volta).: Orstom, Adiopodoumé.