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Modeling the Hydrologic Cycle: The MC Model

Part II – Modeling Applications

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The MC model, developed to simulate the simultaneous movements of surface and groundwater flows in a watershed, is applied to three different types of watersheds to demonstrate its characteristics and its flexibility of use. The first case reports on an application where the surface flow and the groundwater flow are of the same importance, the second case reports on one where the surface runoff dominates and lastly we present a study where the groundwater flows are dominant. In each case, we place emphasis on how the MC model can integrate the hydrological system under study for an accurate representation of reality. Examples of results are also included.

Introduction

Ever since the first hydrological modeling efforts, hydrologists and hydrogeologists have practically always developed mathematical simulation models where respectively surface or groundwater flows predominate. However, in recent years, we have seen mathematical models which, in addition to integrating both types of runoff, take better account of surface and groundwater exchanges. In a previous paper (Deschesnes *et al.* 1985) we have discussed the principles and characteristics of such a model, called the MC model.

In this paper, we demonstrate the possibility for the MC model to adapt to different watershed types, following variable modeling scales. For this we present three application examples where physical and hydrological characteristics as well as the pursued objectives are very different. We do not undertake a complete description of the studies and conclusions reached with the MC model. We do discuss the general objective linked to the utilization of the MC model with special emphasis on its application method and on its capacity to integrate the hydrological system under study for a better representation of reality.

To achieve this we present: 1) an application example where the importance of surface and groundwater flows is equivalent; 2) an example where superficial hydrology dominates and 3) a study where groundwater flow prevails. In each case, we briefly describe the watershed's characteristics and the application's scope. We then describe the modeling process and present the subsequent results.

The MC model is a deterministic mathematical model that integrates precipitation, surface water and groundwater on one or many watersheds. The model's principle is a generalization of the multilayered schematization. The model distinguishes, for one part, a surface layer where available water is parted into surface runoff, infiltration and ground storage by the use of production functions. For the other part, a variable number of groundwater layers, which are eventually connected together, form the vertical succession of the different aquifers. Each layer is afterwards broken into discrete nested meshes of variable sizes to which are given the different system parameters, and on which the water transfers are carried out.

The computation involving the "land type" production functions, defined for each land use, are run at each time interval given by the meteorological data on each homogeneous precipitation zone. A production function which takes into account water bodies is also incorporated into the model. The river network is represented by river meshes which incorporate the two-way exchange between the groundwater table and the river.

Case 1 – Application to the Caramy Watershed (France)

The study area covers approximately 250 km^2 and corresponds to most of the Caramy watershed, a tributary of the Argens river. The study objective is to simulate with a mathematical model the different flow types on the watershed, so that the flow reaching the downstream Carcès lake can be predicted (Girard *et al.* 1981; Ledoux 1980).

Watershed Description

The Caramy river and some minor tributaries drain most of the study area. High water events generally occur towards the end of Fall, during Winter and to a lesser degree at the beginning of Spring. The monthly hydroclimatological data (Table 1) permits the characterization of the regime of this Mediterranean watershed. The calcareous bedrock is covered by a Mediterranean type forest. Important vineyards are found on the alluvial zones and in the bottom of cretaceous depressions.

Table 1 – Caramy watershed: mean hydroclimatological data

	J	F	M	A	M	J	J	A	S	O	N	D	TOTAL
Rain (mm)	141	146	98	72	95	34	33	61	109	129	91	140	1149
ETP Penman (mm)	21	30	55	89	122	153	173	142	89	44	29	22	969
Total runoff (mm)	86	77	67	44	42	22	15	14	14	40	33	55	509

Study Objective

The Carcès reservoir, which collects waters from the Caramy and the Issole rivers, supplies an important part of Toulon's drinking water. However, the water level in the reservoir can get quite low following periods of drought so that meeting water demands becomes problematical.

The situation is further complicated by the impending stoppage of mine water pumping, subsequent to a reduction of the neighboring mining activities. This last supply makes up an important part of the dry weather flow and corresponds approximatively to half of Toulon's average consumption (600 l/s). The MC model is therefore expected to answer the following objectives:

- to determine the impact of groundwater pumping stoppages on a dry weather flows and to study the possibility of sustaining this flow in the future with existing pumping installations;
- to insure a better management of the Carcès reservoir by the choice of the appropriate stock accumulation periods to compensate for low water conditions.

The problem deals with a groundwater river relationship on the watershed where surface flow and groundwater flow are of the same importance.

Modeling

Since the groundwater domain exceeds the Caramy watershed, the model takes into account parts of the Ribeirotte watershed to the north of the Issole watershed to the south and to the east and of the Caramy watershed to the north-west. For the surface layer, three mesh sizes have been used: 1,250, 625 and 312.5 m side respectively. The finer meshes are justified by the watershed's contour and by the course of river, keeping in mind the requirements of surface water-groundwater exchange process. This way, the complete grid of the surface layer holds 615 meshes (Fig. 1).

From the nature of geological outcrops and the land uses we defined six types of production functions adapted to standard "land type" production function (Table 2). The meteorological zones have been established, following the Thiessen's method, from four neighboring rain gauges.

The groundwater flow model takes into account nine aquifer units discretised into square meshes of 1,250, 625 and 312.5 m side. These are represented in Figs. 2 and 3. Relationships between aquifers and the Caramy river are allowed in the 1, 4, 7 and 9 layers.

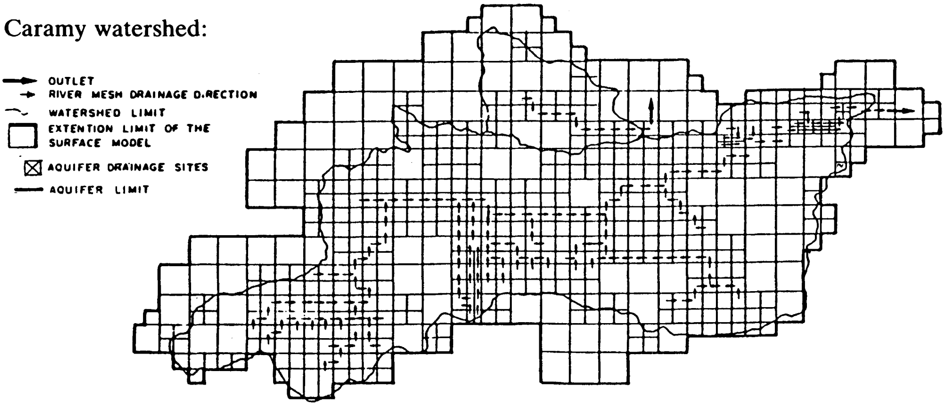

Fig. 1. Surface layer discretisation.

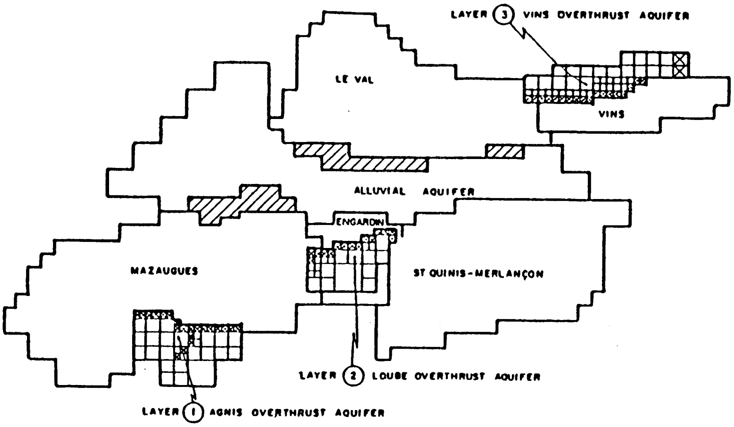

Fig. 2. Discretisation of overthrust formation (layers 1 to 3).

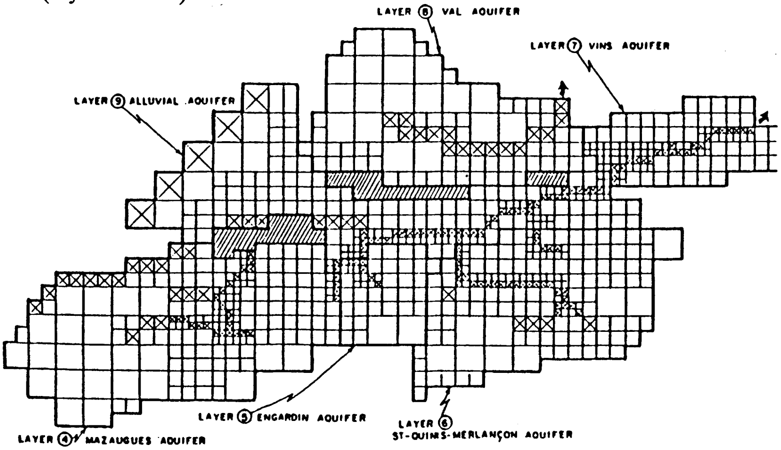

Fig. 3. Discretisation of bottom aquifers (layers 4 to 9).

Table 2 – Caramy watershed: production functions parameter values

Production Functions	Budget Reservoir CRT (mm)	Budget Reservoir DCRT (mm)	FN (mm/day)	Transfer Reservoir QRMAX (mm)	Transfer Reservoir CQR (dimensionless)
1 Valley soil (Caramy Valley)	240	50	10	40	0,2
2 Calcareous-dolomitic soil (in place)	200	60	15	50	0,2
3 Impervious soil (cretaceous)	200	50	0	30	0,2
4 Impervious soil (trias et dogger)	180	40	0	20	0,4
5 Irrigated zones	100	10	0	0	1
6 Calcareous dolomitic soil (imbedded)	160	40	15	50	0,2

Running the Model

According to the model's structure, parameters are calibrated in two steps by which we aim to distinguish as much as possible between the surface and groundwater flows.

The calibration of the surface model is essentially carried out by the MODSUR program. The hydrological budget is established with production functions when the calibration of the two budget reservoir parameters, CRT and DCRT, is accomplished. The partitions between infiltration and surface runoff is related to parameter FN. It must be noted that we have not introduced any aquifer resplenishment reservoir in the production function, because hydrologic investigation suggested that the delay between infiltration and aquifer resplenishment is negligible. A first guarantee of the final representativity of the MC model is obtained by the calibration of the surface model. But this is a provisional calibration. Its validation will be accomplished when the calibration of the groundwater model will be done. Only a complete simulation which takes into account surface runoff, base flow and piezometric variations could entirely confirm the *a priori* conceptual hydrological hypothesis. The calibration process for the MODSUR program, as done for the 1968-1979 period, provides the parameter values listed in Table 2.

The calibration of the groundwater model for the reference period is focused on the reconstitution of the base flow at the hydrometric station for the reference period and on the restitution of piezometric maps and variations of piezometric heads for the different aquifers. The calibration of the base flow is essentially based on its modulation and not on the runoff volumes. The latter has already been preadjusted by the choice of appropriate production functions in the surface model.

Two means are available to adjust the base flow: adjusting the transmissivity (*T*) and the storage coefficient (*S*) of the aquifers or adjusting the groundwater-river communication by the river-water table transfer coefficient (*TP*) and the river infiltration flow rate (Q_0). Breaking down the study area into individual hydrogeologic basins was very helpfull since it permitted an independent calibration of the different aquifers' parameters. A leakage has been considered only in the case of the Vins aquifer (layer 7) and of the Vins over-thrust (layer 3); these necessitated a joint simulation of both aquifers.

The Simulations

Two types of simulations have been done. One on a daily basis to analyze pluviometric data and to bring about a better understanding of the watershed's behavior, and an other on a ten-day basis. This last time step has the advantage of integrating the results of the production functions affected by irregularities in pluviometric data, while still permitting a fine calibration of the model.

Table 3 and Fig. 4 show good agreement between observed and computed annual runoff volumes and hydrographs at the Vins station. The absolute annual gap does not exceed 10% except for 1972 where observations are incomplete. Periods of low and high water are well reproduced. It was not possible to satisfactorily

Table 3 – Caramy watershed: annual computed eand observed runoff volumes at The Vins station (× 10^6 m^3)

		1972	1973	1974	1975	1976	1977	1978	1979	TOTAL
Vins	Computed	20,4*	86,9	160,2	67,2	119,3	145	173,3	105,5	877,7
station	Observed	14,6*	91,8	157,3	59,3	117	135	162,7	91,3	829

* Incomplete year

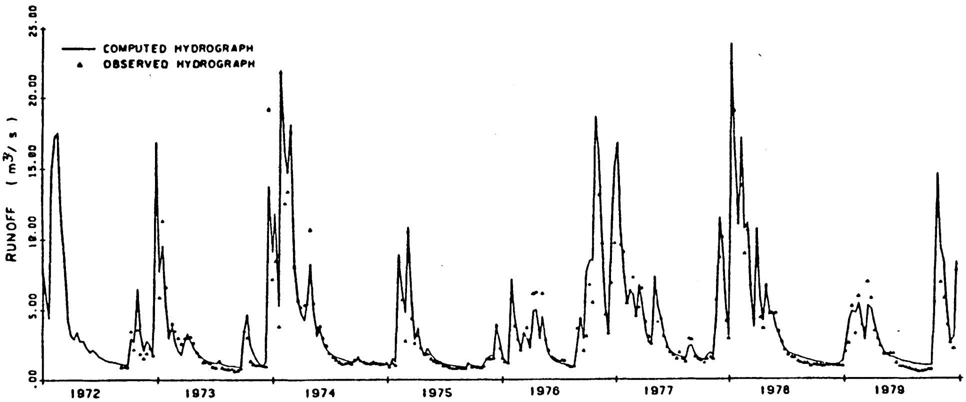

Fig. 4. Caramy watershed: reconstitution of the observed hydrograph at the Vins station.

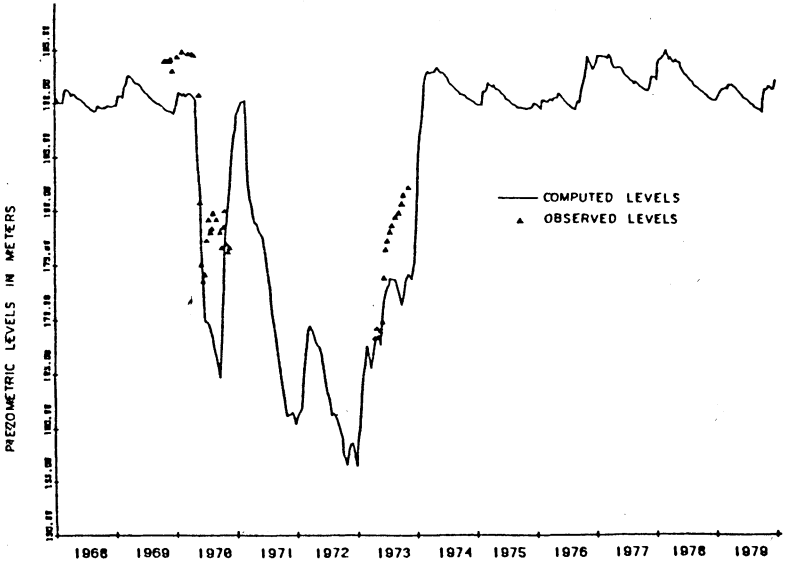

Fig. 5. Caramy watershed: reconstitution of piezometric levels at the Vins 36 piezometer.

restore the piezometric variations for this same period because of the scarcity of piezometric information. For example, Fig. 5 indicates results for the Vins 36 piezometer calibration. The results obtained for runoff simulation as well as for piezometric variations seem to confirm *a priori* the hypothesis that surface and groundwater flows should be modelled jointly on the watershed. However, the model results account for the information gathered at the time of the study and could evolve if new data is supplied later.

We will now discuss a case where watershed hydrology is dominated by superficial flow and for which the data are restricted to a short period.

Second Case – Application to Lake Laflamme Watershed (Québec)

Through this application we try to obtain a synthesis tool based on all previous hydrological studies to confirm and increase our knowledge on the watershed's hydrologic behavior so that future research will be better oriented (Deschesnes 1984; Deschesnes and Villeneuve 1983).

Watershed Description

The Laflamme lake watershed is situated 80 km north of Québec city. Its 68 ha of forested area covers a thin coat of sandy graveled till (of maximal thickness beneath the lake) resting on an impervious bedrock of charnokitic gneiss. The only known exit of water is at the lake's outlet where underground loss is suspected. The

Table 4 – Lake Laflamme watershed: hydrological data

1981	J	F	M	A	M	J	J	A	S	O	N	D	TOTAL
Precipitation (mm)	26.4	235.8	88.2	124.7	124.2	192.4	78.6	190.7	93.6	112.0	47.0	56.0	1369.6
Evapotranspiration PAN "A" (mm)					26.4	112.1	138.5	89.5	56.9				423.4
Observed runoff (mm)	15.6	74.9	38.5	148.1	223.4	108.4	75.2	99.1	39.6	52.9	43.6	24.5	944.1

1982	J	F	M	A	M	J	J	A	S	O	N	D	TOTAL
Precipitation (mm)	111.7	31.5	110.9	95.4	38.8	113.3	96.8	119.2	61.8				779.4
Evapotranspiration PAN "A" (mm)					19.0	110.0	126.9	84.0	48.6				388.5
Observed runoff (mm)	17.4	13.2	14.3	24.7	172.7	58.4	39.3	34.1	33.1				407.2

snowmelt begins in April and reaches its maximum in May when the peak flows are registered. Low water periods are encountered in January and February. Table 4 summarizes the watershed's hydrological observations.

Study Objectives

Since 1980 this lacustrine watershed is the object of extensive hydrological studies, being part of a research program on the impact of acid rain on aquatic and forested ecosystems. One of the program's goals is to constitute an ionic budget and a chemical characterization of waters percolating across the watershed. The MC model is first used to establish a global hydrologic budget so that water movements on the basin can be identified. Because these studies have only started recently, historical data are poor (1½ years of observations). As an inventory and synthesis tool, the MC model is well adapted to this situation. Consequently, this work is a first modeling effort to which we will integrate all future data supplied by the ongoing program. The use of the MC model will bring useful information specially by extrapolating, for some watershed sub-areas, subsurface and superficial discharges as well as hydrologic budgets.

Modeling

The model considers both a surface and a groundwater layer of identical area, which override the basin's limit at the outlet. This means of representation eases the quantification of groundwater volumes running out of the watershed while permitting a simulation of surface discharge at the observation station. The same spatial discretisation for the surface and subterranean domains is used. The grid is

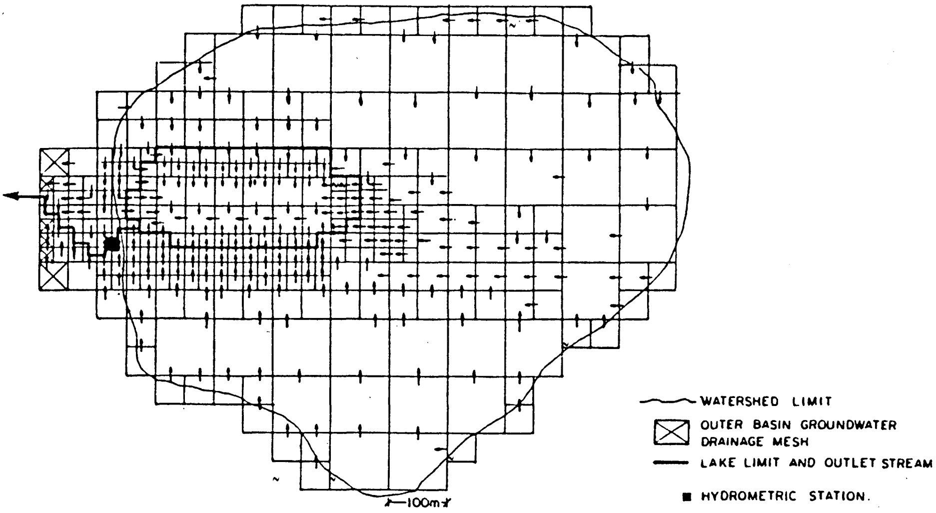

Fig. 6. Lake Laflamme watershed: surface layer discretisation.

formed by three degrees of nested square meshes of 100, 50 and 25 m sides totalizing 309 meshes for each layer (Fig. 6). We used 172 river meshes, represented almost entirely by the smallest ones and on which surface-groundwater exchanges were permitted. We considered two meteorological zones determined by the watershed's east-west orientation (which acts on the snowmelt pattern) rather than by the spatial discretization of rainfall (which is taken as homogeneous over the whole basin). We adapted the "land type" production function only for forested and swampy areas and used the "water body" production function for the lake. We used the drainage conditions for the lake, outlet stream and all river meshes to account for surface-groundwater exchanges. At the outlet, the groundwater flow has been taken up by drain type meshes.

Model Calibration and Results

This step was carried out in two related phases. A calibration of the MODSUR production function parameters was done with the eighteen months of available data with a daily time step. We had to select the best set of parameters to obtain the most representative runoff and infiltration volumes that best fit the observed values. As stated previously, the infiltration values computed at that moment are not independent from the calibration of the MODCOU PROGRAM (river-aquifer relationship, groundwater model). So, the production function parameters were fixed after the MODCOU program have been calibrated. The calibration of the groundwater model was done on the period for which we had piezometric data, i.e. eight months in 1982. This calibration was done on the storage coefficients and the transmissivities.

Table 5 – Laflamme lake watershed: production function parameters values

	Parameter	Forest	Swamp
DCRT	Minimal water stock value in the soil below which no water quantity is available (mm)	2,5	5,0
CRT	Mean water stock value in the soil (mm)	10	25,0
FN	Maximal infiltration value for a given time step (mm)	4,0	1,0
CQR	Surface runoff reservoir depletion coefficient (mm)	0,20	0,15
QRMAX	Surface runoff reservoir overflow level (mm)	30,0	30,0
CQI	Aquifer replenishment reservoir depletion coefficient	0.06	0,03
QIMAX	Aquifer replenishment reservoir overflow level (mm)	30,0	60,0

The calibrated parameter values of the production functions are given in Table 5. We notice that the CRT and the DCRT values are rather low, which indicates a year-round weak flow deficit and a state of high soil saturation. The surface flow reservoir depletion coefficient (CQR) represents a rather slow drain, which corresponds to superficial subsurface runoff conditions. Fig. 7 show that good agreement between observed and calculated hydrographs is obtained for the entire simulation period. The total computed runoff volume (966,000 m^3) is very close to the observed runoff volume (905,000 m^3), representing a 7% overestimation. In general, the restitution of groundwater level sticks well to the observed data. An

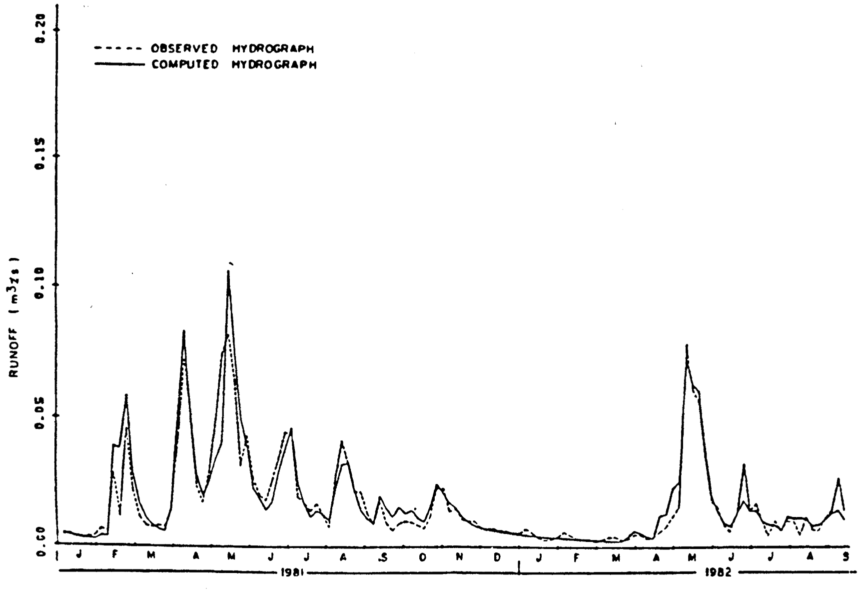

Fig. 7. Lake Laflamme watershed: observed and computed hydrographs at the hydrometric station.

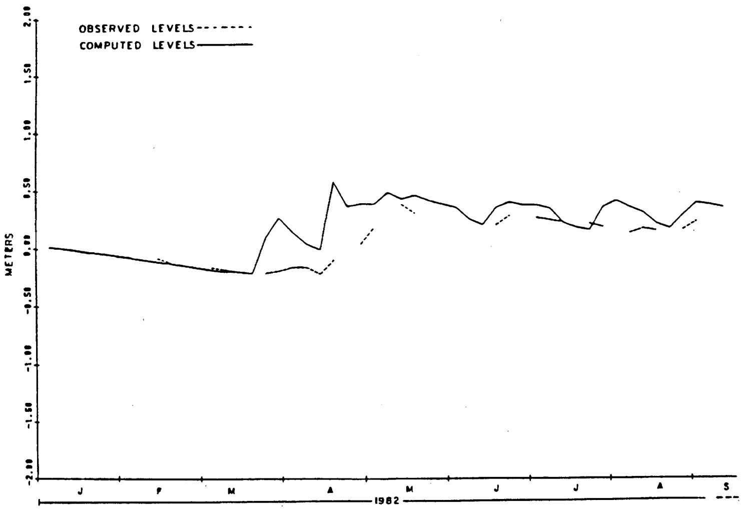

Fig. 8. Lake Laflamme watershed: observed and computed levels at piezometer 3.

example for piezometer 3 is given in Fig. 8. We must take into account that the quantity of the available information for the calibration process limits the model's capacity to conform with reality.

The model still achieved to establish a water budget where the surface runoff component accounts for 55% of total precipitation. Most of the infiltrated water is returned at the surface. Added to the surface runoff component, this represents an outlet flow corresponding to 70% of the precipitation. Groundwater drainage accounts for 8%. These results agree with the observations and confirm the *a priori* hypothesis made on the watershed's hydrological regime.

The third example reports a case for which the MC model was applied to a watershed with prevailing groundwater flow.

Case 3 – Application to the Lys River Watershed (France)

This application stems from a project where low water flow are increased by pumping important water volumes into the Lys river from the basin's underlying aquifers (Besbes *et al.* 1981).

Watershed Description

The Lys river and its principal tributary, the Traxenne, form at Lugy a 85 km^2 watershed. From the geologic and hydrogeologic characteristics we have been able to distinguish two aquifers: the mid-turonian superior groundwater layer which empties itself into valleys by a number of rapidly depleting brooks and, the inferior

Table 6 – Lys watershed: monthly rain and temperature data

	J	F	M	A	M	J	J	A	S	O	N	D	year
Rain (mm)	90	74	80	63	66	59	45	59	91	65	144	104	939
Temperature (°C)	4,6	4,7	5,9	7,7	12,0	14,2	16,3	17,2	14,9	11,8	7,7	5,8	10,2

Cenomanian groundwater layer which has steady flow natural springs. There is a semi-impervious layer between both aquifers thereby permitting some vertical communication. This region's water resource supply comes essentially from groundwater and is naturally drained by the perennial hydrographic network constitued by the Lys and the Traxenne rivers. Monthly precipitation and temperature data for the Lys watershed appear in Table 6.

Study Objectives

Until 1963, neighboring groundwater reservoirs had been supplying drinking water to the city of Lille. Because of increasing demand, it has been necessary to build a water treatment plant to meet the city's 100,000 m^3/d mid-term need which is superior to the low water river flow (30,000 m^3/d). Planners seek to increase the flow by applying different management schemes, one being the seasonal pumping of some of the Haute-Lys aquifer's water into the river. The MC model is intended to simulate the alteration of the natural flow regimen induced by pumping and to help reach the following objectives:

- to determine the aquifer seasonal exploitation yield since the pumping will reduce the natural supplies to the river, but will also induce reinfiltration from the river towards the aquifer in certain areas;
- to determine the aquifer's recharge during periods of pumping stoppage and predict its piezometric state after a number of years of exploitation during low water periods.

The MC model is not run, in this case, to bring information on the description and on the comprehension of the hydrologic behavior of the Haute-Lys watershed but to verify the model's aptitude to adapt to a water resource problem involving a dominating groundwater component and to supply an adequate tool for managing exploitable waters on a watershed.

Modeling

For the groundwater flow model, we consider a superior layer portraying the mid-Turonian aquifer and an inferior layer representing the Cenomanian one. These layers are interconnected by vertical leakage. The surface and the underground basin's limits do not correspond and since the aquifer's areas vary over time, the hydrogeologic limits were expanded to the surrounding main rivers. This way, the

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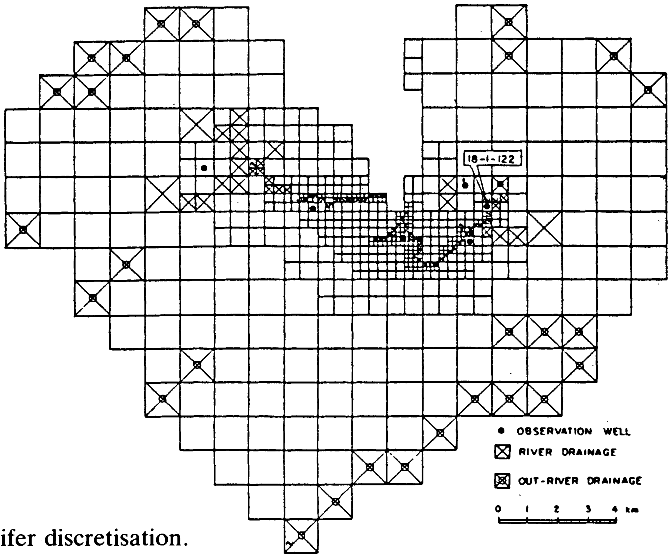

Fig. 9. Mid-Turonian aquifer discretisation.

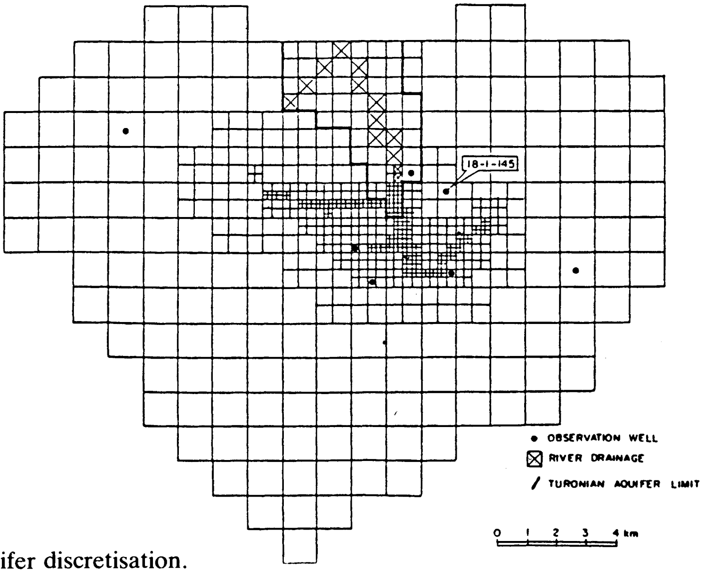

Fig. 10. Cenomanian aquifer discretisation.

model covers a 350 km^2 area. The discretisation of the aquifers plane comprises four levels of divisions using nested square meshes of 1,250, 625, 312 and 156 m sides. The finer meshes were used to represent the Lys and the Traxenne drainage axis. Hence, 1,321 meshes are necessary to discretise the aquifers: 618 for the mid-Turonian and 703 for the Cenomanian (Figs. 9 and 10).

Lys watershed:

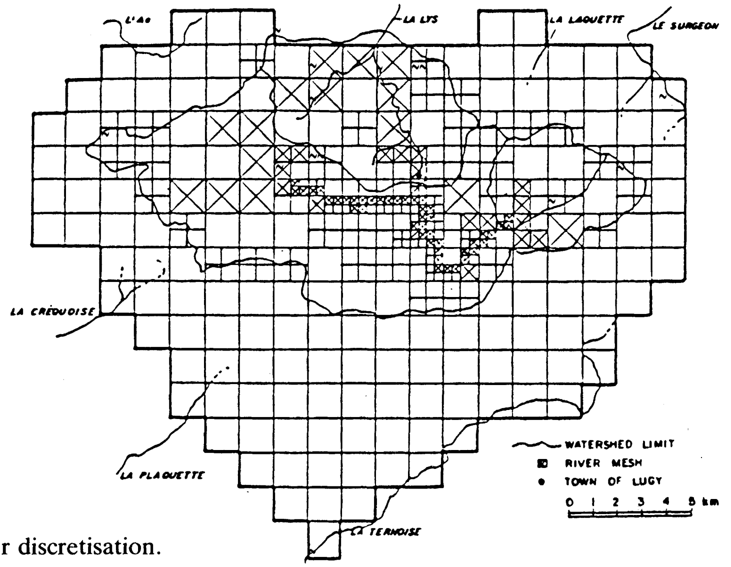

Fig. 11. Surface layer discretisation.

The surface area taken into account by the model covers the mid-Turonian aquifer in totality and the part of the Cenomanian aquifer that outcrops in the Lys valley. This area, which is larger than the Lys-Traxenne basin, is discretised in 424 meshes of 1,252, 625 and 312 m sides (Fig. 11).

Running the Model

The model is run in four steps: the calibration of the groundwater model under steady flow conditions, the calibration of the groundwater model under non-influenced transient conditions, the adjustment of the production functions and the calibration of delay functions (the NONSAT program).

The production functions (MODSUR PROGRAM) were adjusted by comparing on a year basis the discharge volumes calculated and observed at Lugy for the 1971-1978 period. As we already point out with the other examples, a first approach to this adjustment can and even should be done before the groundwater model is completely calibrated, since the infiltration computation is not totally independent from the groundwater state. It must be noted that, because of the small contribution of surface runoff we have not introduced any surface runoff transfer reservoir in the production functions for the simulation.

Groundwater replenishment shows a time lag when supplied infiltration, as computed by the production functions, is compared to the aquifer's piezometric responses. This is taken into account when the NONSAT sub-routine is applied to ten previously determined homogeneous replenishment zones (Besbes and de Marsily 1984) Fig. 12. Table 7 gives the parameter values results for the TAU and N parameters for each of the homogeneous replenishment zones.

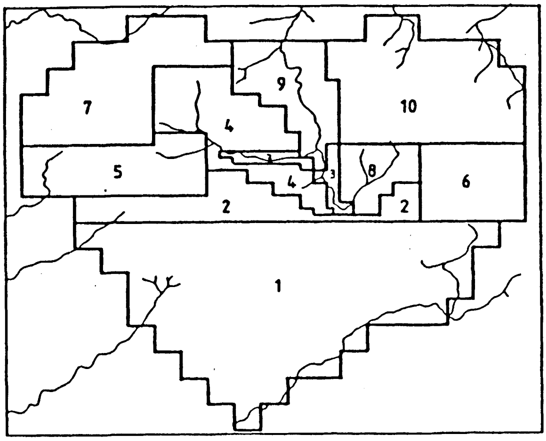

Fig. 12.
Lys watershed: outline of the 10 groundwater replenishment zones.

Table 7 – Lys watershed: NONSAT delay function parameters for each homogeneous replenishment zone

Replenishment zone Number	Number of Reservoirs (N)	Delay (days) (Tau)
1	5	20
2	3	22
3	1	21
4	2	20
5	2	18
6	2	10
7	2	6
8	2	9
9	2	10
10	5	21

The Results

The best results from the MODSUR subroutine calibration are included in Table 8. We note that the reconstitution of the discharge volumes is excellent for the overall period. Also, the absolute deviation remains lower that 8% on a yearly basis. The production functions parameters responsible for these results are given at Table 9. The simulations obtained with the calibrated MC model for hydrometric stations and piezometers correspond very well to the observations. As good examples, we retain the computed hydrograph obtained at the Pont de Lugy station and piezometric levels at the 18/1/122 piezometer of the mid-Turonian aquifer and at the 18/1/145 piezometer of the Cenomanian aquifer (Figs. 13, 14 and 15).

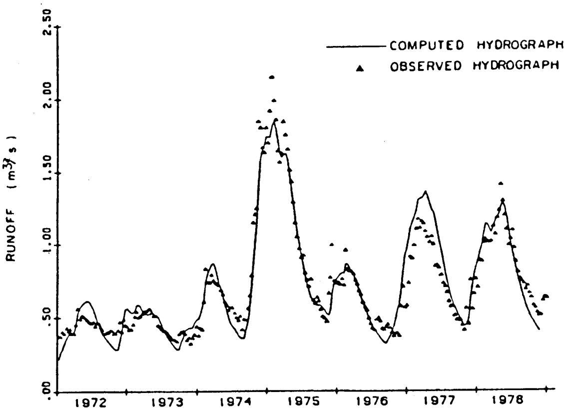

Fig. 13.
Lys watershed: hydrographs of observed and computed runoff at the Pont de Lugy station.

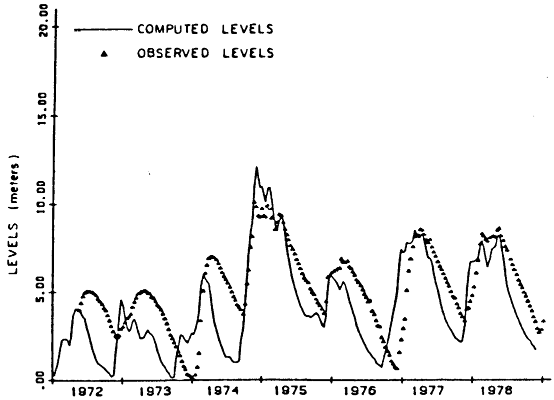

Fig. 14.
Lys watershed: reconstitution of the piezometric levels at the Turonian aquifer, 18/1/122 piezometer.

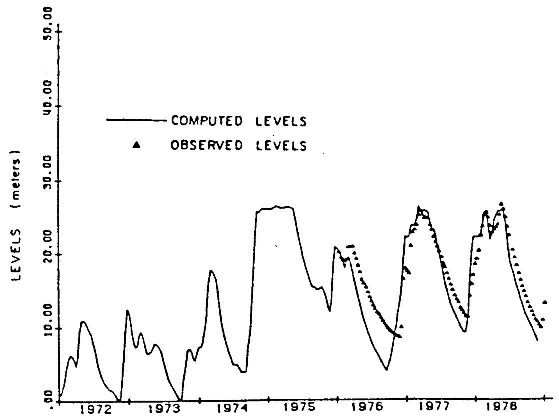

Fig. 15.
Lys watershed: reconstitution of the piezometric levels at the Cenomanian aquifer, 18/1/145 piezometer.

Table 8 – Lys watershed: total runoff at the Pont de Lugy

Volumes 10^6 m^3	1972	1973	1974	1975	1976	1977	1978	TOTAL
Observed	13,6	13,6	23,1	36,4	18,1	25,2	26,3	156,3
Computed	13,3	14,3	21,7	34,8	18,1	27,3	28,6	158,1

Table 9 – Lys watershed production functions parameters

Land Type	DCRT (mm)	CRT (mm)	FN (mm/d)
Agricultural soil	10	60	30
Forest	10	80	30
Bushwood	10	60	30
Marches	100	150	10
Impervious Areas	10	50	10

This application demonstrate the MC model's aptitude to adapt to simulation problems with a dominating groundwater component, as long as the model includes a detailed representation of groundwater flow, a good estimation of infiltration as well as a good calibrated sub-routine to account for the infiltration time lag.

Conclusion

The MC model, which covers most of the hydrological cycle main components on one or more watersheds, takes into account more information about the watershed's physical structure and hydrological phenomenon than models which treat groundwater and surface water separately. This partially compensates for the scarcity of data and increases the level of confidence over the computed water budget and runoff volumes.

The three MC model applications we have discussed in this paper demonstrate how its design and more specifically its means of discretisation using nested square meshes of variable sizes, makes it a very flexible tool which can be adapted to various hydrological situations and modeling scales. We have also shown that despite insufficient information (especially piezometric data) it is possible to obtain a reliable means for computing river discharges. For each application, the values on computed runoff volumes never exceeded 10% of those observed values. The second application also demonstrated the possibility to begin the modeling at an early stage of the hydrological study period and to add new data and information in the model as they become available.

Hence, we believe that in its present form, the MC model is an appropriate tool to help define, orient and sustain the water manager's studies and decisions involving both surface water and groundwater. However, the model is not restricted to its present computerized form and can be improved to respond more accurately to other practical problems. For example, the surface component has been improved to take into account dam reservoir systems. A future evolution could be the integration of mass transport phenomena into the model.

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