Nordic Hydrology, 16, 1985, 257-272

Modeling the Hydrologic Cycle: The MC Model

Part I – Principles and Description

J. Deschesnes and J.-P. Villeneuve
INRS-Eau, Sainte-Foy, Québec, Canada

E. Ledoux and G. Girard
École nationale supérieure des mines de Paris, France

This article discusses the joint modeling of surface and groundwater flows by presenting and describing the MC model. The purpose of this deterministic physically based model is to simulate the behavior of available water resources for one or many watersheds. The model integrates surface flow, streamflow, flow in the non-saturated zone, groundwater flow and the interactions between rivers and water tables. Its formulation and its structure, especially its nested square meshes of variable sizes, confer a great deal of flexibility to the model; this facilitates adaptation to variable modeling scales and to a wide range of geological, geographical and climatological conditions.

Introduction

One of the earliest and very simple hydrological model is the quantitative expression of flood magnitudes in relation to rainfall and watershed area known as the rational formula (Mulvaney 1851). Since then, further progress in basic and applied hydrology has contributed to a better understanding of the terrestrial components of the hydrological cycle. This, in turn, supported by an increase in computation capabilities, permitted the development of more realistic hydrological models.

Today, many types of deterministic physical based watershed models are reported in the literature. These models can be included in one of two main categories: streamflow-overland flow models and groundwater flow models. In the surface flow models, the groundwater flow is partially treated and often taken into account with a lumped parameter. This category is valid where groundwater does not constitute an important part of the overall flow domain. The Stanford Watershed Model (Crawford and Linsley 1966), the SSARR model (U.S. Army Corps of Engineers 1975), the CEQUEAU model (Morin *et al.* 1981) and MDOR (Villeneuve *et al.* 1984) are a few examples of this type of model. Fleming (1979) presents a good review of many surface models.

The second category is used where groundwater resources dominate. In groundwater models, overland and streamflow are treated as boundary conditions and may even be completely neglected. Many groundwater models have been built and are widely used (Bachmat *et al.* 1980). The Prickett and Lonquist model (1971), the model put forward by Trescott et al. (1976) and Newsam (Ledoux and Tillie 1980; Ledoux 1975) are a few examples.

However there is a watershed category where surface flow and groundwater flow are closely linked together. In these watersheds, both the surface water and groundwater and their interactions are of a significant importance and their proper management requires that both be studied simultaneously. It is therefore necessary, in these cases, to use a hydrological model that simulates the conjunctive use of surface water and groundwater, and their interactions, in a realistic way. In using such a model one has the advantage of taking into account all water contributions to the hydrological basin as well as the eventual interactions between the water cycle's terrestrial components. This type of model constitutes an adequate tool for the efficient control of the water budget components and has proved very useful to answer questions raised by regional water resources problems associated with surface water and groundwater (Hansen and Dyhr-Nielsen 1983). For example, such a tool can enable the study of the effects of aquifer abstraction on surface water regimen, particularly during low-water periods (Miles and Rushton 1983; Refsgaard and Hansen 1982b; Besbes *et al.* 1981; Emsellem 1971).

This article discusses the joint modeling of surface flow and groundwater flow by presenting the MC model. We first look at the general characteristics for this type of model and then we will describe the MC model structure and formulation. Note that the expression *MC model* is the English transposition of the model's French name *M*odèle *C*ouplé.

Characteristics of Integrated Flow Models

Obviously, the model cannot represent all the mechanisms involved in the hydrological cycle and, to avoid undue complexity, must simplify reality by integrating only its principal components. The aim of modeling is to estimate the total flow at the outlet of the watershed. It is recognized that total flow is a combination of three processes: surface flow, interflow and base flow (Fig. 1). We are also interested in

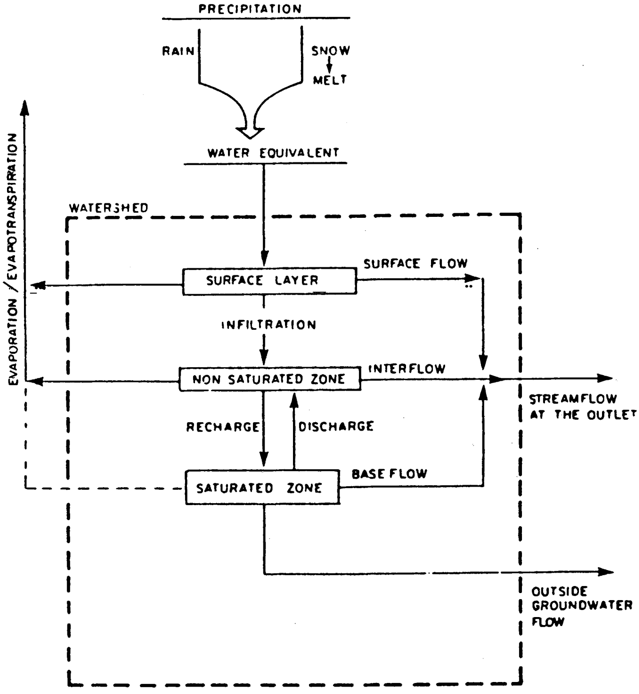


Fig. 1. Schematization of the principal components of an integrated flow model.

the eventual interactions between these hydrological processes and the systems' environment (Fig. 2): exchanges with the atmosphere, surface outflows, lateral contribution by surface water, exchanges between aquifers and exchanges between the non-modelled surface areas and aquifers.

However, in addition to the integration of the main processes and relations, the model should, for economic and operational considerations, satisfy particular characteristics (Freeze and Harlan 1969; Jacquet 1971). First, the model must take into account the system's physical properties. The model's representation of the system must be based on the maximum amount of geological, geomorphological, topographical and physiographical information. In addition, the functions used in describing the hydrological processes must be derived from known physical law or include conceptual functions in which parameters represent a physical reality. Because the model is indeed an image of the system's physical structure, simulation results can be interpreted with an increased level of confidence.

Second, the model must represent the spatial and temporal variations in the system's structure and behavior. This condition is relevant to the variability of hydrological phenomena and to the model's usefulness as a tool for planning, development and management purposes. In most cases, modeling work is not concerned with the conditions that prevail at the monitoring stations themselves:

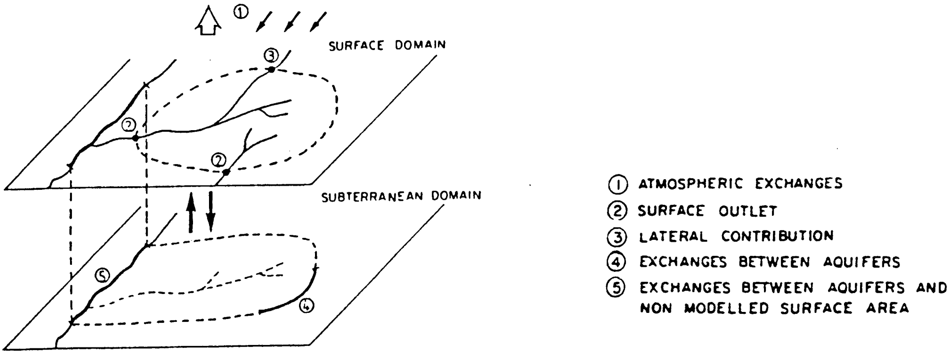


Fig. 2. Schematization of the relations between the model and the system's environment (after Ledoux 1980).

the tool must therefore be helpful in extrapolating the watershed's response to points where there may be particular needs.

Third, the model must be suitable for a vast range of hydrological and geographical conditions. In practice this is desirable because it imparts a great deal of versatility with respect to the model's eventual applications to different hydrological system configurations. The model must use a minimum number of parameters for calibration and must incorporate simple relations to represent the hydrological processes so that its usefulness is unhindered when going from one watershed to another.

Furthermore, it is preferable to use a model that can be easily adapted to data obtained at different levels of discretisation at any time of the modeling process. This permits 1) to use the model as soon as the minimum amount of data required to run the program is collected; 2) to update the model as new information and data become available. This gives, for example, the modeler the possibility of progressively defining areas where particular studies have to be undertaken to respond more accurately to the objectives of the modeling study.

Since the model is to be applied by users who have not worked on its design, it is necessary as Bachmat *et al.* (1980) point out, that the model be supplied with a set of relevant documents, including a complete description of the model, a user's manual, print out copies of the program and modeling examples.

Existing Integrated Flow Models

Until now, much attention has been focused on management models that integrate the use of surface water and groundwater with respect to economic, technological and political objectives (Bachmat *et al.* 1980). In watershed hydrology, the first attempts at modeling the interaction between surface and groundwater flows were aimed at the study of the hydrologic cycle's mechanisms and to the development of new tools to improve hydrologic methods and research. Pinder and Sauer (1971) were the first to present a model that treats alluvial-aquifer-stream interactions to calculate the modification of a flood wave due to bank storage effects. Freeze (1972) introduced a deterministic mathematical model that couples three-dimensional transient saturated-unsaturated subsurface flow and one-dimensional gradually varied unsteady channel flow to study the role of subsurface flow in generating storm runoff.

In practice, usable models have been built for various objectives according to two approaches. The general approach includes models conceived and designed to be applied to watershed of variable sizes and characteristics. The Knapp *et al.* (1975) model is a very good example of an integrated watershed flow model designed to be general in practice. However, it should be noted that it requires the estimation of a relatively large number of parameters ($\simeq$ 40). Another example is the Cunningham and Sinclair (1979) coupled flow model involving the simultaneous numerical solution of the surface and subsurface flow equations using the Garlekin finite-element method. It includes specific methodologies worked out by Pinder and Sauer (1971).

The second approach is more specific to a particular watershed's physical characteristics. With this approach, model application is restricted to watershed where the general configuration and the physical characteristics are similar. The main objective of the model reported by Refsgaard and Hansen (1982a) was to predict the hydrological consequences of groundwater abstraction on the river discharges and on the hydraulic heads of the aquifers for the Suså watershed in Denmark. Miles and Rushton (1983) discussed a model that represents surface and subsurface flows of water to assess the long-term water resources of a particular watershed in England.

In the following section, we will present the underlying principle and the structure of a new integrated flow model. The MC model, whose phenomenological conceptualization is based on the generalist approach, is a versatile tool that can be easily adapted to most hydrologic situations that may occur in practice.

Presentation of the MC Model

The MC model's objective is to simulate the behavior of available water resources in one or many watersheds. The model takes into account streamflow, overland flow, flow in non-saturated zone and in saturated zone (the latter may integrate multilayered aquifers), and considers exchanges between surface water and water tables.

The model is the result of work undertaken by INRS-Eau (Villeneuve and Leblanc 1978), O.R.S.T.O.M. (Girard *et al.* 1972) and the Centre d'informatique géologique (C.I.G.) de l'École nationale des mines de Paris (Ledoux 1975; 1980).

The approach used in developing the MC model was to break down the water cycle components into independent steps that can be checked individually. Thus the model is made up of five distinct but interconnected functions which deal with one or more components of the water cycle. They are the entry function (responsible for water inputs into the system), the production function (responsible for the distribution of inputs in infiltration, evaporation, surface flow and storage), the surface transfer function, the groundwater tranfer function and the surface/water tables transfer function. The model presently integrates these functions into four programs written in FORTRAN and operated sequentially: GEOCOU, MODSUR, NONSAT and MODCOU.

The GEOCOU Sub-Routine

Using geographic, physiographic and geologic information, the GEOCOU program defines the surface and subterranean areas to be modelled. The model retains one surface layer from which the watershed's limits are set, and a variable number of subterranean layers as justified by the geologic and the hydrogeologic analysis of the modelled area. Each layer is then discretised with nested square meshes of variable size according to available information and to modeling objective (de Marsily *et al.* 1978; Ledoux and Tillie 1980) (Fig. 3).

Then, according to topography, a single drainage direction is assigned to each mesh. We thus obtain a surface drainage network made up of the river network (represented in the model by river meshes) and the runoff zone network (represented in the model by meshes whose outlets are a river mesh). The computation of river-water table exchanges are carried out only on river meshes. Computation of infiltration and surface flow are allowed for meshes of the runoff zone network.

This distinction between the two networks reduces the required computational task by restricting full use of the model's capabilities to areas of real necessity. Of course, there are other possible configurations including the extremes: 1) a configuration limited to groundwater flows (where no river meshes are considered) would only require the computation of infiltration and 2) a total watershed area aquifer/river exchange configuration would mean that the whole drainage network is assigned to river meshes.

Finally, each mesh of the surface layers is assigned to a pluviometric station that defines a meteorological zone of homogeneous precipitation and to a homogeneous land use area.

The MODSUR Sub-Routine

This program gives, for the surface layer, the proportion of precipitation that goes to infiltration or to surface runoff evaluated by production functions. A first computation of outlet volumes is also made in this program. Input data taken into account are precipitation, evapotranspiration and watershed concentration time (Ledoux 1980).

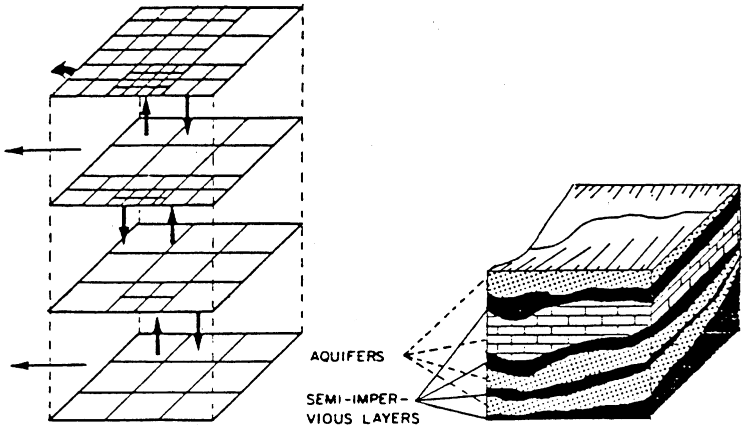
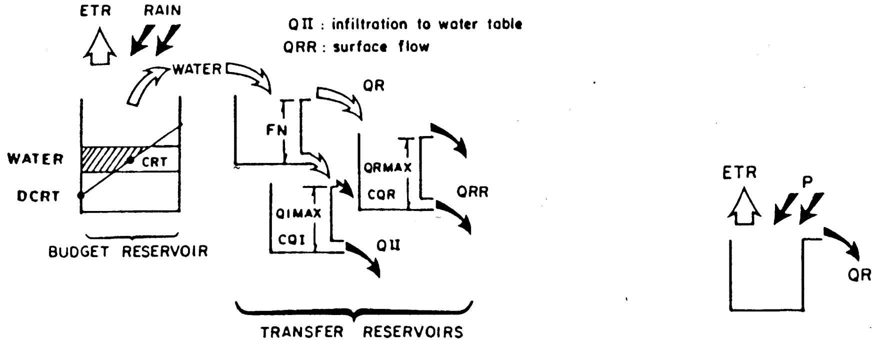


Fig. 3. Schematization of the spatial discretisation of the MC model.



DCRT	Minimal water stock value in the soil below which no water quantity is available (mm)
CRT	Mean water stock value in the soil (mm)
FN	Maximal infiltration value for a given time step (mm)
CQR	Surface runoff reservoir depletion coefficient (mm)
QRMAX	Surface runoff reservoir overflow level (mm)
CQI	Aquifer replenishment reservoir depletion coefficient
QIMAX	Aquifer replenishment reservoir overflow level (mm)

A) Diagram of the "land" type production function

B) Diagram of the "water body" type production function

Fig. 4. Standard diagrams of the MC model's production functions.

The production function represents the part of the non-saturated zone where the water budget is established. Two standard production functions (Fig. 4) incorporated into the model are simplified approaches belonging to the reservoir model category (Girard *et al.* 1972). Experience has shown that this approach is a strong one: i.e. with analogous application conditions, a straightforward transposition of parameter values from one watershed to another leads to satisfying results (Ledoux 1976).

Each production function remains linked to a specific homogeneous zone of precipitation and land use identified during the surface discretisation step. For the "land type" standard production function, the modelled mechanisms are the same for bare land or for land covered by any type of vegetation: only the parameters describing these mechanisms are liable to change. The water budget is computed at each time step and is a function of precipitation (P), evapotranspiration (ETR) and storage state of the reservoir (R). The water available for transfer (WATER) is then determined by two parameters, DCRT and CRT, representing respectively the minimum and the average water quantity within the budget reservoir. The first transfer reservoir distributes the available water (WATER) between runoff (QR) and infiltration by means of the infiltration parameter FN. Two other reservoirs eventually cause a delay for infiltrated water and surface runoff. If necessary, however, the delay between infiltration and water table replenishment can be taken into account more accurately by the NONSAT program.

The "water body" production function is applicable to surface water bodies of non negligible area. The water bodies may or not may be the part of the river network. In the model's present form water body area does not vary with reservoir water height.

The computation of runoff on the runoff zone network is accomplished for each mesh of a computation sub-basin by the use of a tranfer algorithm based on the notion of isochronism (Villeneuve and Leblanc 1978) Fig. 5, according to the formula

$$Q_i^j = \sum_{k=1}^{n} QR_k^{j-k+1}$$

where

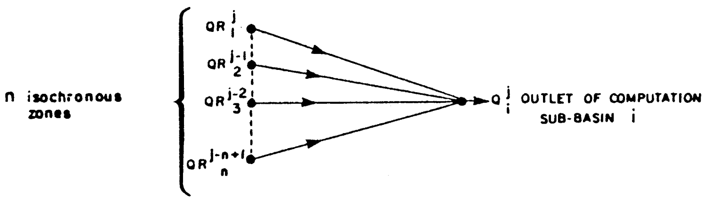


Fig. 5. Transfer algorithm for a computation sub-basin.

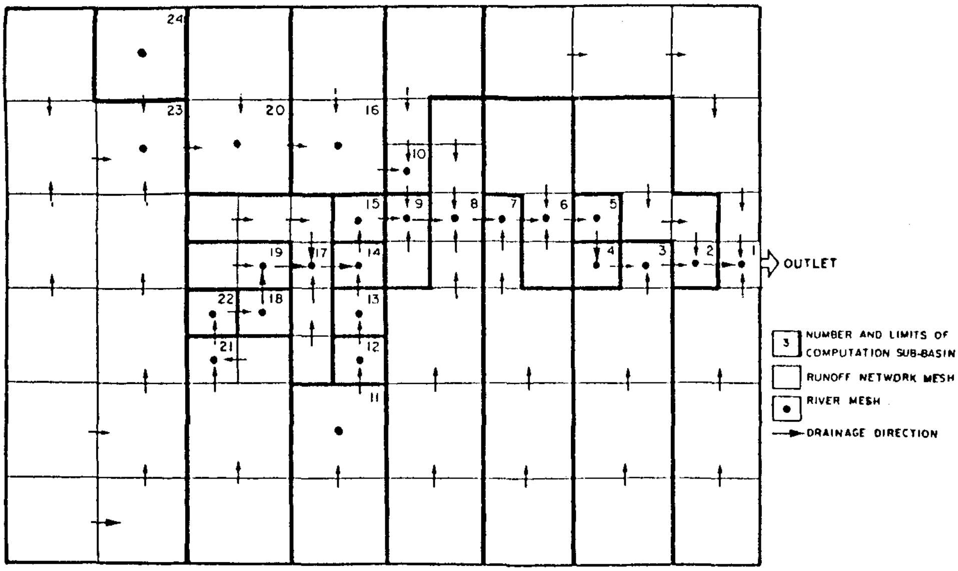


Fig. 6. Schematization of the definition of computation sub-basins.

Q_i^j – volume of runoff at time step j for the computation subbasin i;
QR_k^{j-k+1} – computed volume available at time step $j-k+1$ for the k^{th} isochronous zone;
n = total number of isochronous zones.

A computation sub-basin groups meshes of the runoff zone network that exhibit the same transfer time to the outlet and eventually discharge into a river mesh (Fig. 6).

In addition, the MODSUR program does a first tranfer of water coming from the computation sub-basins to the watershed's outlet. This enables a first approximation of the runoff and infiltrated water volumes and a adjustment of the concentration time.

The NONSAT Sub-Routine

This program accounts for the time-lag between infiltration volumes computed by the MODSUR program and the groundwater replenishment for each meteorological time step. This is done by grouping meshes into homogeneous zones with respect to the tranfer in the non-saturated zone according to Nash's principle (Nash 1959) and proposed by Besbes (1978) (Fig. 7). If the non-saturated zone is fragmented into homogeneous strata of equal thickness and if the permeability between two strata is unique, then, the number of reservoir (N) represents the

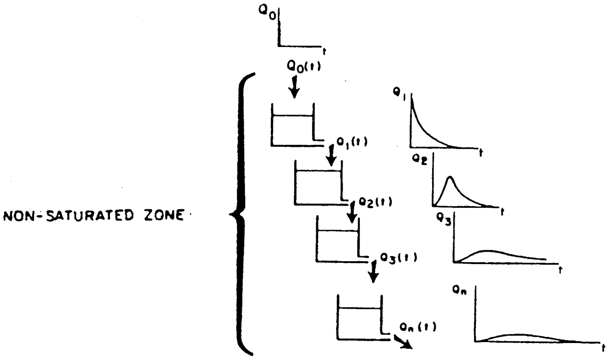


Fig. 7. The principle of the Nash model.

thickness of the non-saturated zone and the depletion reservoir coefficient (*TAU*) is related to the vertical permeability of that zone.

The definitive adjustment of this program is done at the end of the simulation, usually with the aid of piezometric level patterns.

The MODCOU Sub-Routine

The MODCOU sub-routine is the final step in the modeling process and is the MC model's most important component. It simulates water transfer in both surface layer and aquifers and takes into account interactions between rivers and water tables (Ledoux 1980).

The groundwater model represents the flow of water for multilayered systems and is described by the classical equation

$$\mathrm{div}(\bar{\bar{T}}\ \mathrm{grad}\ h) = S\frac{\partial h}{\partial t} + q + q_{\mathrm{sup}} + q_{\mathrm{inf}}$$

where

h – hydraulic head $[L]$;
$\bar{\bar{T}}$ – transmissivity tensor $[L^2]\ [T^{-1}]$;
S – storage coefficient;
q – flow by unit volume withdrawn from or injected into the medium; also will take into account water flow rate exchanged with surface layer $[L]\ [T^{-1}]$;
$q_{\mathrm{sup}}\ q_{\mathrm{int}}$ – flow rate exchanged between aquifers layers throughout semi-impervious strata $[L]\ [T^{-1}]$.

The solution of the system of equations for the entire modeled area is found iteratively by the point-successive over relaxation method following implicit or explicit schemes according to the time-step chosen for computation.

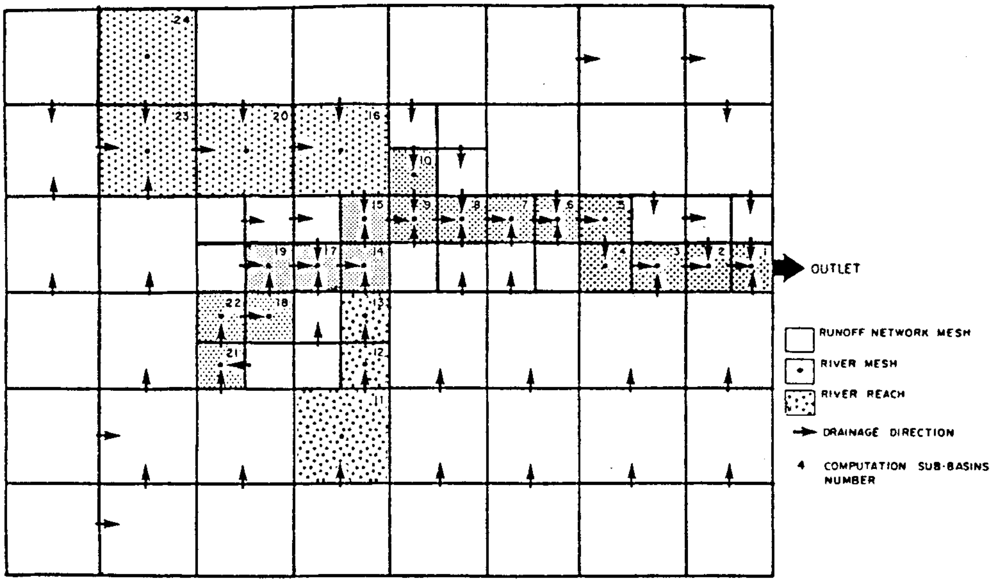


Fig. 8. Schematization of the grouping of river meshes into river reaches.

The multilayered hydrogeological system is composed of a number of layers representing aquifers in which water movement is allowed in the horizontal plane, and a number of interbedded semi-impervious layers for which flow is considered as vertical only (de Marsily *et al.* 1978; Bredehoeft and Pinder 1970) (Fig. 3.).

River transfer takes into account waters originating from the sub-basins and from river-water table exchanges. This transfer is acheived by establishing a series of river reaches that discharge into one another following an exponential depletion law. River reaches are established by grouping river meshes that have the same time-lag to the watershed's outlet (Fig. 8). If V_i^j is the water volume stocked in river reach i at time step j, then this volume becomes at time step $j + 1$ (Fig. 9)

$$V_i^{j+1} = (1-XKB_i)(V_i^j + QR_i^j + QNAP_i^j) + \sum_{k=1}^{N} XKB_k\,(V_k^j + QR_k^j + QNAP_k^j)$$

where

QR_i^j – amount of available water at time step j from computation sub-basins flowing into river reach i;

$QNAP_i^j$ – water volumes exchanged between river meshes belonging to river reach i and the water table at time step j;

XKB_i – drainage coefficient for river reach i.

The river aquifer relationship is computed at each time step between river

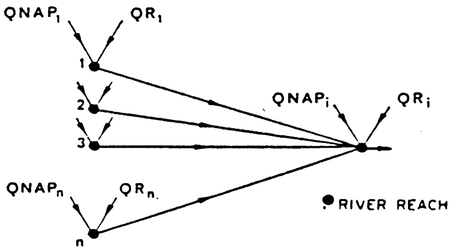


Fig. 9. General diagram of transfers between river reaches.

meshes associated with those describing the water table. Two situations are allowed (Fig. 10): in the first one, the river and the water table are connected. The river head may or may not be greater than the aquifer's head and water loss or gain for the river is evaluated by the equation

$$QNAP = TP(H_0 - H)$$

where

H – piezometric head $[L]$;
H_0 – river head $[L]$;
TP – seepage coefficient accounting for head loss between river and water table.

In the second situation, the river and the water table are not connected. In this case, we admit that water transfer is allowed from the river to the water table with a known flow value limited by the water stock of the concerned river mesh

$$QNAP = Q_0$$

Thus, during the low water period we may go from situation 1 to situation 2 and then return to situation 1 during the following flood period.

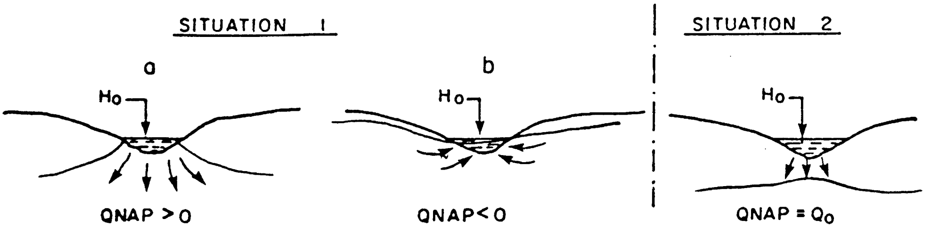


Fig. 10. Schematization of the aquifer-river relationship.

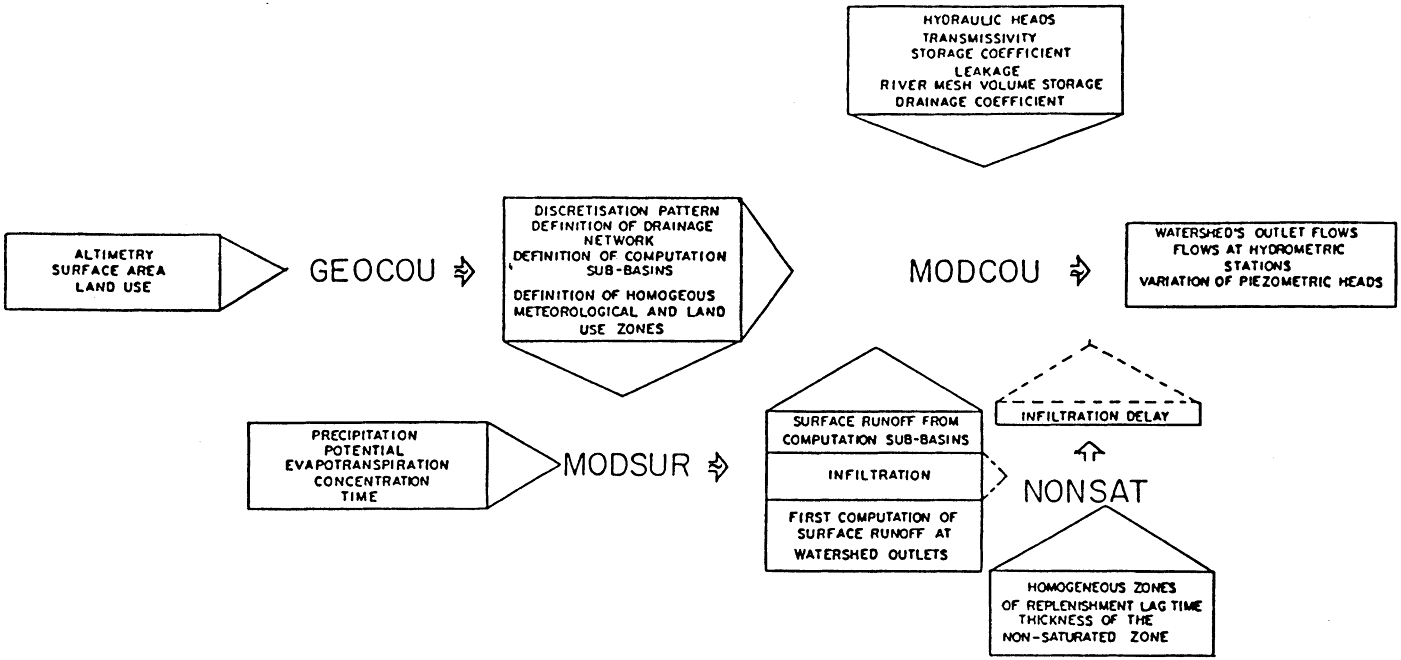


Fig. 11. Input data, principal outputs and sequential organization of the MC model's subroutines.

Conclusion

Today, many deterministic models are specific to either surface or groundwater hydrology. Because modeling both surface flow and groundwater flow simultaneously has only recently (1970) drawn interest, few models of this type are presently usable over a wide range of geographic and hydrologic watershed characteristics and modeling scales. To have these properties we discussed that a model must be physically-based, have a good discretisation means and incorporate simple relations, with few parametres to be adjust, that represents the main components of the terrestrial hydrological cycle.

The purpose of the model presented in this paper is to simulate both surface runoffs and groundwater flows. The MC model formulation and structure take into account the geographic and geologic configurations of the modeled area and the main components of the terrestrial hydrologic cycle: surface flow, streamflow, flow in the non-saturated zone, groundwater flow (including multilayred aquifers) and interactions between rivers and water tables. Fig. 11 summarizes the sequential organization of the model's sub-routines.

The use of nested square meshes of variable sizes as discretisation means imparts a great deal of flexibility to the model. The discretisation pattern can represent the geologic, physiographic and climatologic heterogeneity and enables the modeler to take into account, at any time of the modeling study and at any level of discretisation, any information reliable to improve the modeling results. The equations describing flow patterns are physically based and pertain to well-known hydrological concepts. Some mechanisms as the groundwater flow, are described by well known equations but others, like the infiltration process, are too complex and have been modeled with parametric functions that includes few parameters that need to be adjusted. The model require input data that are readily available for most watersheds (precipitation, evapotranspiration, concentration time, transmissivities, storage coefficients).

These structure and formulation ease the MC model use over a wide range of geologic, physiographic and climatologic configurations including extreme cases where the surface network is absent or where groundwater flow is unimportant.

The second part of this two article series presents three practical studies that illustrate the MC model's capability to adapt to different problems for watersheds of variable sizes and characteristics.

References

Bachmat, Y., Bredehoeft, J., Andrews, B., Holtz, D., and Sebastian, S. (1980). Groundwater management: the use of numerical models, Water resources monograph, series 5, American Geophysical Union, Washington, D. C., 127 p.

Besbes, M. (1978). L'estimation des apports aux nappes souterraines. Un modèle régional d'infiltration efficace. Thèse d'état, Université Pierre et Marie Curie, Paris VI.

Besbes, M., Duermael, B., Ledoux, E., De Marsily, G., and Talbot, A. (1981). Soutien des étiages d'une rivière par pompage dans la nappe qu'elle draine: mythe ou réalité? Bulletin du B.R.G.M. 2 (III).

Bredehoeft, J. D., and Pinder, G. F. (1970). Digital analysis of areal flow in multiaquifer groundwater systems: a quasi three-dimensional model, *Water Resources Research, Vol. 6*(3), 883-888.

Crawford, N. G., and Linsley, R. K. (1966). Digital simulation in hydrology: Stanford watershed model IV. Dept. of Civil Engineering, Stanford University, tech. rep. no. 39, 220 p.

Cunningham, A. B., and Sinclair, P. J. (1979). Application and analysis of a coupled surface and groundwater model, *Journal of hydrology, Vol. 43,* 129-148.

Emsellem, Y. (1971). Modèles mathématiques pour la gestion intégrée des ressources en eau, Ecole nationale supérieure des mines de Paris, Centre d'informatique géologique, rapport R/71/6.

Fleming, G. (1979). Deterministic models in hydrology, FAO irrigation and drainage paper, Rome 80 p.

Freeze, R. A. (1972). Role of subsurface flow in generating surface runoff; 2. Upstream source areas, *Water Resources Research, Vol. 8* (5), 1273-1283.

Freeze, R. A., and Harlan, R. L. (1969). Blueprint for a physically – based digitally – simulated hydrologic response model, *Journal of Hydrology, Vol. 9,* 237-258.

Girard, G., Ledoux, E., and Villeneuve, J. P. (1981). Le modèle couplé: simulation conjointe des écoulements de surface et des écoulements souterrains sur un système hydrologique, Cahiers ORSTOM, série hydrologie, *XVIII* (4).

Girard, G., Morin, G., and Charbonneau, R. (1972). Modèle précipitations – débits à discrétisation spatiale, Cahiers de l'ORSTOM, série hydrologie, *9*(4), 35-52.

Hansen, E., and Dyhr-Nielsen, M. (1983). Le projet du Suså: construction de modèles pour la gestion des ressources en eau. Unesco, Nature et Ressources, *XIX*(3).

Jacques, J. (1971). Aspects généraux de la représentation mathématique des phénomènes en hydrologie de surface, La houille blanche *2:* 104-110.

Knapp, R. M., Green, D. W., Pogge, C., and Stanford, C. (1975). Development and field testing of a basin hydrology simulator, *Water Resources Research Vol. 11*(6), 879-888.

Ledoux, E. (1980). Modélisation intégrée des écoulements de surface et des écoulements souterrains sur un bassin hydrologique, Thèse de doctorat, École nationale supérieure des mines de Paris et l'Université P. et M. Curie, Paris VI, 236 p.

Ledoux, E. (1975). Programme Newsam. Principe et notice d'emploi, Rapport École des mines, LHM/R75/11.

Ledoux, E., and Tillie, B. (1980). Programme Newsam. Principe et notice d'emploi, version 1980, École nationale des mines, LHM/RD/21/40.

Ledoux, E., Levassor, A., Charbonneau, R., Morin, G., and Villeneuve, J. P. (1976). Simulation des débits de l'Orne, la Dives et la Seulles, Coopération franco-québécoise, INRS-Eau.

Marsily, G. de, Ledoux, E., Levassor, A., Potrinal, D., and Salem, A. (1978). Modeling of large multivariated aquifer systems: theory and applications, *Journal of Hydrology, Vol. 36,* 1-34.

Marsily, G. de, Frasnetti, J. C., Ledoux, E., Tiburtini, R., and Villeneuve, J. P. (1977). Inventaire des ressources en eau et adéquation besoins – ressources: peut-on faire une première approche simplifiée à partir d'une modélisation complète du cycle de l'eau? Colloque national "Les eaux souterraines et l'approvisionnement en eau de la France", Nice.

Miles, J. C., and Rushton, K. R. (1983). A coupled surface water and groundwater catchment model, *Journal of Hydrology, Vol. 62,* 159-177.

Morin, G., Fortin, J. P., Lardeau, J. P., Sochanska, W., and Paquette, S. (1981). Modèle CEQUEAU, manuel d'utilisation, INRS-Eau, rapport scientifique no 93, 449 p.

Mulvaney, T. J. (1851). On the use of self-registering rain and flood gauges in making observations of the relations of rainfall and of flood discharges in a given catchment, *Trans. Inst. Civil Engrs. Ir. (Dublin) Vol. 4*(2): 18.

Nash, J. E. (1959). Systematic determination of unit hydrograph parameters, *Journal of Geophys. Res., Vol. 64*(1).

Pinder, G. F., and Sauer, S. P. (1971). Numerical simulation of flood wave modification due to bank storage effects, *Water Resources Research, Vol. 7*(1), 63-70.

Prickett, T. A., and Lonquist, C. G. (1971). Selected digital computer techniques for groundwater resource evaluation, Illinois state water surv. bull., *55,* 62 p.

Refsgaard, J. Chr., and Hansen, E. (1982a). A distributed groundwater / surface water model for the Suså-Catchment, Part I: model description, *Nordic Hydrology, Vol. 13,* 299-310.

Refsgaard, J. Chr., and Hansen, E. (1982b). A distributed groundwater / surface model for the Suså-Catchment, Part II: simulation and streamflow depletions due to groundwater abstraction, *Nordic Hydrology, Vol. 13,* 311-322.

Trescott, P. C., Pinder, G. F., and Larson, S. P. (1976). Finite difference model for aquifer simulation in two dimensions with results of numerical experiments. Techniques of water resources investigations of the U. S. Geol. Surv. book, 7, chap. cl., 116 p.

U. S. Army Corps of Engineers (1975). Program description and user manual for SSARR – streamflow synthesis and reservoir regulation. U. S. Army engineer, division North Pacific Portland, Oregon, Program, 724-K6-60010.

Villeneuve, J. P., Isabel D., and Houle, S. (1984). Le modèle de simulation hydrologique MDOR, Rapport scientifique no 163, INRS-Eau.

Villeneuve, J. P., and Leblanc, D. (1978). Algorithme de schématisation des écoulements d'un bassin versant, Rapport interne no 62, INRS-Eau.

Received: 5 September, 1985

Address:
Jean Deschesnes and
Jean-Pierre Villeneuve,
INRS-Eau,
Case Postale 7500,
Sainte-Foy, Québec,
Canada G1V 4C7.

E. Ledoux and M. G. Girard,
C. I. G.,
École nationale supérieure des mines de Paris,
35 rue St-Honoré,
77305 Fontainebleau,
France.