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SEMI-GLOBAL HYDROLOGICAL MODELLING BY COUPLED SIMULATION OF THE VARIATIONS OF WATER STORAGE IN THE UNSATURATED ZONE AND OF THE PIEZOMETRIC LEVEL EVOLUTION

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Abstract. A new type of hydrological model -called "semi-global" has been created to attempt at a better understanding of the physical behaviour of a drainage basin. This model, called "Gardensol" simulates the basin globally, in its spatial extension, but it reproduces, at least approximately, the real phenomena with physical parameters capable of being measured in the field :

- vertical permeability at saturation,
- residual water content, corresponding to an almost nil vertical infiltration permeability.

As it can be calibrated simultaneously on the water content variations in the unsaturated zone and on the piezometric variations, the model is much more reliable and more robust than a rainfall-aquifer level model where the aquifer levels are reproduced only from a usually badly known storage coefficient. The estimation of the recharge, in particular, must be much more exact and the model can be used by extending data to analyse the resource fluctuations according to the climatic variability.

Three application examples are given :

- coupled simulation of the water storage in the unsaturated zone and of the piezometric level at Mézières-les-Cléry (Loiret department, France),
- simulation of the water storage during 8 years in a small area of the Orgeval experimental basin of the CEMAGREF,
- coupled simulation of the water storage in the unsaturated zone and of the piezometric level on the Lille-Sainghin (France) experimental site.

Keywords. Hydrology ; models ; unsaturated zone ; water resources data processing ; parameter estimation.

INTRODUCTION

The rainfall-runoff and rainfall-aquifer level lumped hydrologic models are used classically to extend the data in a drainage basin or to estimate the natural recharge of an aquifer by the rain. The **Gardenia** (Roche and **Thiery**, 1984) hydrological tank model, for example, enables the reliable simulation, from 4 lumped parameters, of the discharge of a stream or a spring at the outlet of a drainage basin. It makes a model possible, from 6 lumped parameters, of the level variation at one point of an aquifer recharged by rainfall (**Thiery**, 1988a).

After calibration of the parameters of the model on the piezometric level observations, the groundwater recharge value can be obtained. This kind of model is, in fact, doubly lumped :

- lumped for the spatial extent ; as it is considered that a whole basin is described by the same parameters ;
- lumped in its working, for the model parameters cannot be measured in the field and convey global phenomena.

The model parameters can therefore, only be determined by calibration on series of observations. Thus, it may happen that several sets of parameters produce almost identical simulations, in a normal period, but risk to give different results in reaction to extreme climatic conditions.

Various applications -in particular **Thiery** (1987, 1988c)- also show that, in the case of slowly varying groundwater, whose storage coefficient is badly known, a satisfactory calibration can sometimes be obtained for several sets of parameters if data of surface run-off on the drainage basin are not available.

To remove the indetermination, a semi-global model -the **Gardensol** model- was created with support of the ECC. This model is called semi-global since, although the spatial extent of the basin is represented globally, the flows through the unsaturated zone are simulated -approximately at least- by simplified physical laws whose parameters have physical dimensions and could be deduced from field experiments or measurements :

- vertical permeability at saturation,
- water content at saturation,
- residual water content (corresponding to a very strong suction),
- water content corresponding to an almost nil permeability.

The model parameters can thus be predetermined approximately and adjusted so as to be able to reproduce simultaneously the recording of variations of piezometric levels in the groundwater, or of discharge at the basin outlet, and those of water storage (or of average water content) in a given width of the unsaturated zone.

Models like that described by **Rambal** (1987) or by **Johansson** (1987), also enable modelling of the water storage variations, but the originality of the **Gardensol** model is that it enables the simultaneous modelling of the evolution of the water storage in the unsaturated zone and of the piezometric level at one point in the groundwater. The model is much more reliable and robust than a classic rainfall-aquifer level one, which reproduces levels only from a generally badly known storage coefficient. The recharge assessment must be much more reliable, in particular, and the model can be used to extend the data for analysing the resource fluctuation according to the climatic variability.

FLOW DIAGRAM OF THE GARDENSOL MODEL

An unsaturated soil may be described by two characteristic relations of the state of saturation :
- a permeability/water content relation,
- a suction/water content relation.

In practice, these relations generally take the form :

$$K = Ks \left(\frac{\theta - \theta r}{\theta s - \theta r} \right)^{b_k} \qquad (1)$$

$$h = ht \left(\frac{\theta s - \theta r}{\theta - \theta r} \right)^{b_t} \qquad (2)$$

where K = permeability $[LT^{-1}]$
Ks = permeability at saturation $[LT^{-1}]$
θ = volumetric water content $[L^3/L^3]$
θs = volumetric water content at saturation $[L^3/L^3]$
θr = residual volumetric water content $[L^3/L^3]$
h = pressure (= -suction) $[L]$
h_t = pressure at half-saturation $[L]$
b_t) b_k) exponents

To obtain integrable solutions, very simple laws have been chosen.

Percolation

$b_k = 1$ was chosen, i.e. that the permeability decreases linearly from the Ks value at saturation to a value of 0 for a water content θk. Moreover a unitary gradient was supposed in all cases.

$$PERC = K = Ks\ (\theta - \theta k)/(\theta s - \theta k) \quad \text{if } \theta > \theta k \qquad (3)$$

$$PERC = 0 \quad \text{if } \theta \leq \theta k$$

where $PERC$ = percolation
θk = water content corresponding to an almost nil permeability

Evapotranspiration

To take account of the fact that the suction increases when the water content decreases and partly counterbalances the decreases in permeability, a linear decrease of the actual evapotranspiration with the saturation state was supposed :

$$FL_{AET} = FL_{PET}.(\theta - \theta r)/(\theta s - \theta r) \qquad (4)$$

where
FL_{AET} = actual evapotranspiration flow $[LT^{-1}]$
FL_{PET} = potential evapotranspiration flow $[LT^{-1}]$

Run-off

The upper soil layer of a basin generally gives rise to a "retention" phenomenon (partly due to interception by vegetation and in the depressions at the surface of the soil). This possible phenomenon can be simulated by a (low) interception capacity. When the possible interception capacity is saturated, the run-off has been chosen proportional to the water content of the soil :

$$FL_{RU} = FL_{INFIL}.CRU.(\theta - \theta r)/(\theta s - \theta r) \qquad (5)$$

where
FL_{RU} = run-off flow $[LT^{-1}]$
FL_{INFIL} = infiltration flow = $R - FL_{PET}$ $[LT^{-1}]$
R = rainfall flow $[LT^{-1}]$
CRU = run-off coefficient $[-]$

A certain thickness, TH, of soil, is considered. The water conservation equation can, therefore, be written :

$$TH.\frac{d\theta}{dt} = FL_{INFIL} - PERC - FL_{AET} - FL_{RU} \qquad (6)$$

By replacing the right-hand terms by their expression given by equations (3) to (5) a differential equation is obtained. This, being linear, can be solved exactly without time discretization. Only the boundary limits (rain flow, PET flow) are discretized at fixed time steps.

The diagram for basin simulation is :

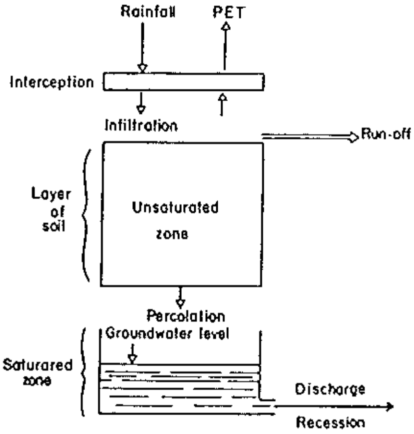


Fig. 1. Gardensol model - Flow diagram

EXAMPLES OF APPLICATION

Three application examples are given :
- coupled simulation of the water storage in the unsaturated zone and of the piezometric level at Mézières-les-Cléry (Loiret, France),
- simulation of the water storage during 8 years in a parcel of the CEMAGREF experimental basin of Orgeval (France),
- coupled simulation of the water storage in the unsaturated zone and of the piezometric level on the Lille-Sainghin (France) experimental site.

Example 1 - Experimental basin of Mézières-les-Cléry (Loiret)

The Mézières-les-Cléry experimental basin lies a few kilometres from Orléans (France) and was equipped in 1979 and 1980 to monitor the migration of industrial muds into the ground, as part of a contract with the french Ministry for the Environment (**Sauter**, 1980, **Barrès** and **Sauter**, 1985). A test parcel (not influenced by the muds) was equipped with 8 tensiometers distributed from 20 cm to 175 cm below the ground surface. The water contents were also recorded, by neutron probe, every 20 cm, over a depth of 240 cm, 20 times from June 1979 to November 1980.

Drilling showed that the soil was composed of 20 cm of top soil, then 10 metres of sand and gravel (red sand), followed by 7 metres of marl, overlying the aquitanian limestone. A borehole located nearby enabled monitoring of the underlying groundwater during the 5 years of the 1979-1983 period. For this period, 107 level measurements are available, i.e. approximately 2 measurements per month. During this period, the levels were at depths of between 12 and 15 metres. The groundwater was locally slightly confined near the sites but unconfined and recharged not far away by the rain through soil with the same characteristics.

A calibration was made by adjusting the model -at a daily time step- simultaneously on the piezometric series and the water storage series of the layer between 0 to 2.4 m depth. The rainfall figures used are those recorded at Mézières from May 1979 to December 1983. The values required for the initialization of the calculations, (January 1978 to April 1979), as well as a few missing values, were taken from the recordings of the Météorologie Nationale at Orléans-Bricy. The monthly potential evapotranspiration was calculated by the Turc formula (**Turc**, 1961) with the Orléans data. The integration of the minimum and maximum humidity profiles correspond to storage of between 283 mm and 335 mm, i.e., on an average, for a section of 2.4 m, to a minimum water content of 11.8 % and maximum of 14.0 %.

Figure 2 shows that a very good adjustement is obtained :

- correlation coefficient = 0.94 with the levels,
- correlation coefficient = 0.93 with the water storage.

The parameters identified are :

- Surface zone	
. retention (and interception) capacity :	5 mm
- Unsaturated zone	
. water content at saturation :	15.8 %
. water content of nil permeability :	12.4 %
. residual water content :	12.0 %
. permeability at saturation :	$8.1\ 10^{-8}$ m/s
- Saturated zone (groundwater)	
. time for half-recession :	5 months*
. storage coefficient :	8.2 %
. local base level :	17.00 m beneath ground level

The mean annual balance for the 5 years 1979-1983 can, therefore, be written (in mm/year) :

- rain	761	
- actual evapotranspiration	-	386
- surface run-off	-	0
- infiltration	-	383
- storage difference	8	
TOTAL	769	769

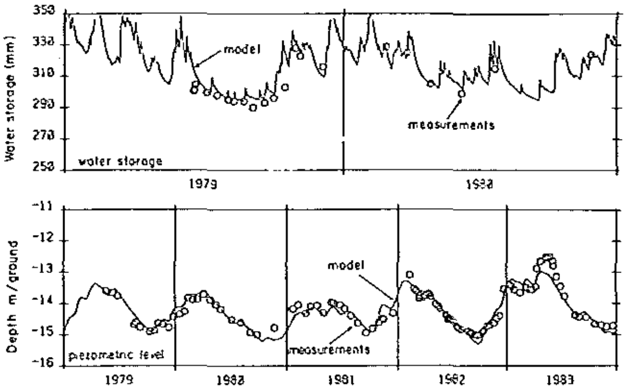


Fig 2- SITE OF MEZIERES LES CLERY

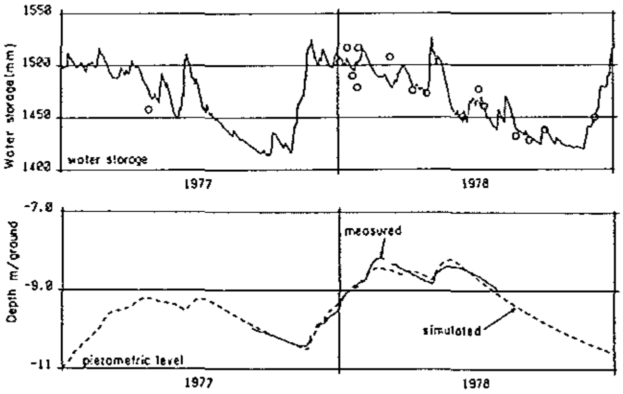


Fig: 3 - SITE OF LILLE - SAINGHIN

Exemple 2 - Lille-Sainghin site

The site of Sainghin en Mélantois, 8 km south-west of Lille, was monitored by the BRGM in 1977 and 1978 as part of the study contracts 76-0-1131 and 76-0-1132 with the Direction générale à la Recherche Scientifique et technique (General Directorate to Scientific and Technical Research) (**Ausseur and others**, 1979). Measurements were taken in the unsaturated zone from the ground and in a 1.8 m-diameter and 8.3 m-deep well. The water content was measured every 20 cm in depth by a neutron probe. The piezometric levels were recorded continuously in two observation wells (P2 and P3), 100 m from the measuring well, but only the data of observation well P2 -the most regular- were used in this application example. Model calibration was carried out by adjusting the model, at a daily time step, simultaneously on the 305 piezometric level observations and on the 16 values of water storage from 0 to 4 m below the soil surface. The rainfall used is that recorded on the same site (completed in 1976 by the Lille rainfall for the initialization of the model states). The potential evapotranspiration was calculated by the Turc formula with the mean Lille climatic data.

* i.e. a transmissivity of $1.8\ 10^{-3}$ m^2/s for a distance of 1 km from an outlet.

Figure 3 shows a good adjustment both on the levels (correlation : 0.89) and on the water storage (correlation 0.91). The parameters identified during this application are :

- Surface zone
  - . retention (and interceptio) capacity : 31 mm
- Unsaturated zone
  - . water content at saturation : 43.6 % (1,743 mm for 4 m)
  - . water content of nil permeability : 36.3 % (1,451 mm for 4 m)
  - . residual water content : 32.4 % (1,297 mm for 4 m)
  - . permeability at saturation : 2.4 10^{-7} m/s
- Saturated zone (groundwater)
  - . time of half recession : 5.7 months*
  - . storage coefficient : 4.9 %
  - . local base level : 12.38 m/ground

*i.e. a transmissivity of 9.2 10^{-4} m^2/s for a distance of 1 km from an outlet.

The annual water balance of the 1977-1978 period is given in table 1.

TABLE 1 Mean hydrological balance, in mm/year of the 1977-1978 period at Lille-Sainghin

- rain	625	
- actual evapotranspiration	-	438
- surface run-off	-	0
- infiltration	-	178
- storage difference	-	9
TOTAL	625	625

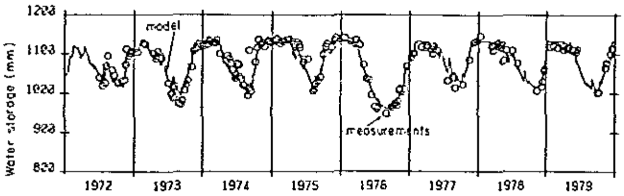
Example 3 - Orgeval basin (sub-basin of Mélarchez)

The water storage data come from tube n0. 10 of the Boissy-le-Chatel parcel (C. **Loumagne**, 1984). This drained parcel (drains 0.70 m under the ground) of 615 m2 which has no appreciable surface run-off, is part of the Mélarchez sub-basin (7 km2), included in the CEMAGREF's experimental basin of the Orgeval. The water contents were recorded 200 times by neutron probe down to a depth of 3.05 m during the 8 years of the 1972-1979 period. The water storage data of this very long series and the daily rainfall data recorded from 1971 to 1979 at Boissy-le-Chatel, were kindly provided by CEMAGREF. The potential evapotranspiration is that calculated during the same period by the Turc monthly formula, with data recorded in Paris.

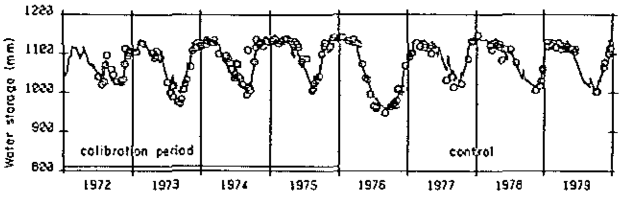
Calibration -on the 200 water storage measurements- enabled a good adjustment (correlation coefficient : 0.95), as is shown in figure 4a. To check the reliabilty and the robustness of the model, two other calibrations were carried out over 4-yearly periods : 1972-1975 and 1976-1979. Figures 4b and 4c show that a model calibrated on 4 years allows a good simulation of the storage of the 4 other years. The prediction capacity of the model can be appreciated by means of Nash's efficiency criterium (EC) (**Nash and Sutcliffe**, 1979) defined by :

$$EC^2 = 1 - s^2/E^2 \qquad (7)$$

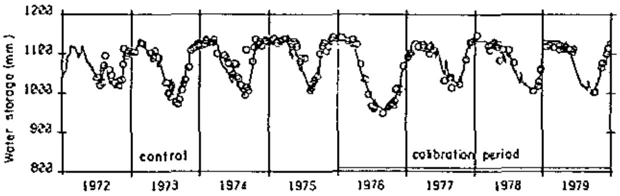
where : s^2 = mean quadratic deviation over the control period
E^2 = mean quadratic variation of the storage observed over the control period, compared to the mean storage over the calibration period



a) Calibration on the whole 1972/1979 period



b) Calibration on the 1972/1975 period



c) Calibration on the 1976 /1979

Fig:4 -WATER STORAGE ON THE MELARCHEZ PARCEL,ORGEVAL BASIN

The identified parameters are described in table 2.

TABLE 2 Calibration parameters of the model on the Mélarchez site

	Calibration period		
	1972/1979	1972/1975	1976/1979
- Surface zone			
. retention and interception capacity (mm)	55	56	67
- Unsaturated zone			
. water content at saturation %	39.7	39.6	39.1
. water content of nil permeability %	35.4	35.6	35.0
. residual water content %	30.7	30.6	30.8
. permeability at saturation m/s*	7.4 10^{-4}	9.9 10^{-4}	8.6 10^{-4}
. adjustment coefficient	0.951	0.936	0.970
. nash efficiency criterium	-	0.866	0.928

*This high permeability value must not be taken as an absolute value, considering the drains which are responsible for the decrease in the water storage.

The application shows that the model enables a good simulation of a long series with, in particular, very dry years (1976 had a very low storage) and wet years (1972, 1978, 1979). The simulation is distinctly better than which would be obtained with a single model with a retention capacity that dries up in the same way every summer.
The mean annual balance of the 8 years, 1972-1979, is given in table 3.

TABLE 3 Mean annual balance (in mm/year) of the 1972-1979 period

- rain	669	
- actual evapotranspiration	-	520
- surface run-off	-	0
- infiltration	-	120
- storage difference	-	29
TOTAL	669	669

CONCLUSION

The Gardensol model, which is described in this paper, enables a correct representation of the water content variations of ground exposed to rain, evapotranspiration and natural drainage. It thus enables a simultaneous assessment of the water content variations in the unsaturated zone and the piezometric level variations in the underlying groundwater. Three application examples were presented and a study of robustness showed that the calibration is stable since a calibration carried out over 4 years (at Mélarchez-Orgeval) enabled the accurate extrapolation of the water contents over the other 4 years. The model can, therefore, be used for extending the data so as to determine -after calibration over a few years of observations- the resource variability from a long series of climatic data. Other more recent applications (e.g. Bonin and Thiery, 1988) confirmed this model's interest. In the cases, though quite rare, where there are also available data of suction measurements in the unsaturated zone and permeability data in the unsaturated zone, it is surely more interesting to use e physical model according to Richards law like that described by Thiery (1988b) even though it is more delicate and time consuming.

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