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Modelling the aquifer recovery after a long duration drought in Burkina Faso

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Abstract The water level in an observation well in Ouagadougou (Burkina Faso) in a granite environment has been monitored for 13 years. The water level has been analyzed with a lumped-parameter rainfall-level hydrological model. The model simulates the aquifer level through a daily balance between the observed rainfall data and the estimated potential evapotranspiration and is calibrated by comparison with the observed levels. In 1988 the model was calibrated on the eight years data, when the declining trend of the level was observed. After calibration and calculation of the confidence limits the model was used for the simulation of a groundwater level response to more abundant rainfall. In 1992, when five further years of records were available, the model was used again without any recalibration. It appeared that the model, though calibrated during a declining period, was reliable and could predict very accurately the stabilization of the decline and the beginning of the rise. This case study demonstrate clearly the efficiency of lumped-parameter hydrological model in analyzing the sensitivity of aquifers to droughts.

INTRODUCTION

Hydrological models are very useful to analyze natural aquifer levels and to predict the influence of changes in the climate. However, it is important to determine to what extend this kind of model is reliable and may be used in conditions different from the calibration period. This question is particularly crucial in arid climates which display a strong variability.

A long period of records is available at an observation well bored to a depth of 20 m in a granite aquifer in Ouagadougou (Burkina Faso). The well is screened from 6 to 20 m, and taps 5 m of granitic sand, 4 m of weathered granite, and 5 m of fresh granite. It has been monitored since 1978 by the ICHS, which has recorded data covering an eighth-year period from 1978-1985. These data were subject to detailed analysis using a lumped-parameter model, with the aim to extend the data sequence. The scope of this paper is to present a sensitivity analysis of the predictions of the model and to control their validity by comparison with observations.

AVAILABLE DATA

Piezometric levels

The water levels in the ICHS observation well in Ouagadougou were manually monitored by the ICHS between 1978 and 1991 (Diluca & Muller, 1985). The records show a continuous fall in the average levels, passing from a depth about 6 m below the surface in 1978 to just over 10 m in 1985. Since then, the level gradually rose by about 1 m within 5 years. A second observation well situated about one kilometre apart has been monitored by IWACO since 1983. The correlation coefficient between the 2 series of levels is equal to 0,93, the amplitude of ICHS observation well being 61% of the amplitude of ICHS observation well. Comparison of both series is shown in Fig. 1, with IWACO series being transformed into the amplitude of the ICHS series. The high degree of correlation shows that the levels have a regional representativity and are not influenced locally by abstractions (trees or pumping).

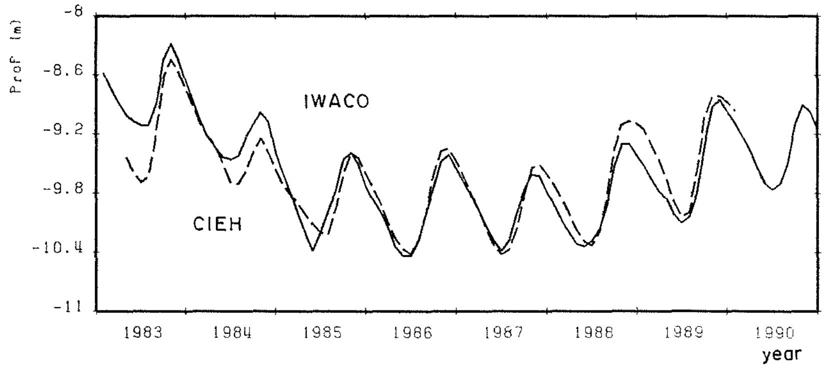

Fig. 1 Ougadougou aquifer level. CIEH/ICHS observation well (solid) compared to IWAKO well (broken line).

Hydrodynamic characteristics

No data are available in particular, the storage coefficient is not known, although it can be estimated at between 1 and 8% on the basis of the rock composition.

Rainfall

Daily rainfall figures from 1959 to 1991 (33 years) were provided by ORSTOM and ICHS. Average annual rainfall was 825 mm in the period 1959-1985, but only 690 mm in the period 1978-1985.

Potential evapotranspiration (PET)

The monthly values needed by the model were calculated using Turc's formula with Ouagadougou data. Only the interannual means were available (Lemoine & Prat, 1972). The total annual PET is 2084 mm.

THE LUMPED-PARAMETER MODEL USED

The GARDENIA model developed in BRGM was used to calculate the balance of rainfall, potential evapotranspiration, runoff and infiltration. This lumped-parameter hydrological model makes it possible to produce a local balance in daily time-steps, and to calculate the actual evapotranspiration (AET), runoff, infiltration, and the water-table level. The model is described in detail by Roche & Thiery (1984), Boisson & Thiery (1990). It may be used for simulation of runoff at the outlet of a drainage basin or of the aquifer level variation at one observation well. It may also be used for forecasting (Thiery, 1988). The basic principles of the model are shortly reviewed below.

Operational principle

The GARDENIA model consists of three superimposed layers (Fig. 2). The first (RU) is characterized by its retention capacity (RUMAX) (or maximum soil moisture deficit), and represents the retention effect in the first few metres below the surface. This layer is recharged by rainfall, and is emptied by evapotranspiration. Neither runoff nor infiltration occur before this layer is saturated. The first layer takes also account of effects caused by the interception in surface depressions.

The second layer (H) is characterized by two parameters - half-percolation time (THG) and runoff level (RUIPER). This layer transfers water to the water table through the unsaturated zone, and controls distribution between runoff and infiltration. The higher the level in this layer, the greater is the runoff proportion. When the level of the layer is equal to RUIPER, infiltration equals runoff.

The third layer (G) is characterized only by the half-recession time TG, and

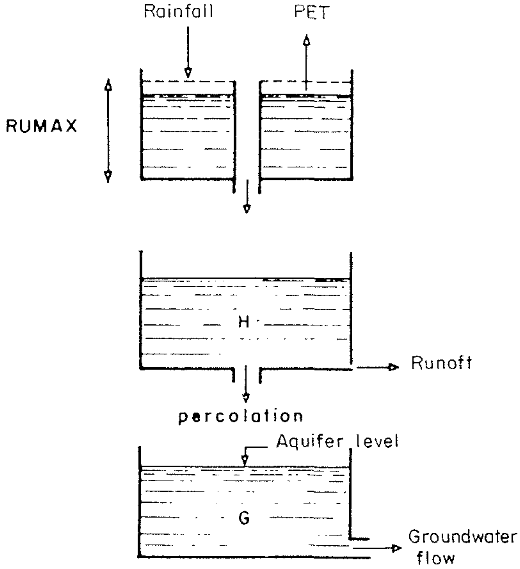

Fig. 2 Principles of the GARDENIA model used to simulate piezometric levels.

represents exponential aquifer recession. This scheme corresponds approximately to an aquifer bounded on one side by an impermeable barrier and on the other by a prescribed-level barrier. If the observation well is positioned sufficiently far away from the imposed-level boundary, the piezometric level is deduced from the level G in this layer by the formula:

$$PL = G/STOR + BL$$

where PL is the piezometric level, G is the level in the layer, STOR is the unconfined storage coefficient or specific yield, and BL is the base level

Six parameters are therefore to be determined:

(a) the retention capacity (RUMAX), which controls the value of potential evapotranspiration (PET),
(b) the half-percolation time (THG),
(c) the runoff level (RUIPER) which, associated with THG, controls the runoff proportion and the delay-time between excess water in the soil and a rise in the aquifer level,
(d) the half-recession time (TG) which governs the rate of aquifer recession,
(e) the base level (BL),
(f) the storage coefficient or effective porosity (STOR).

CALIBRATION OF THE MODEL

In 1988 when 8 years of records were available spanning the time interval 1978-1985, the model was calibrated (see Thiery, 1990a, 1991). It appeared that, due to the slow reaction of the aquifer, it was not possible to determine a unique set of parameter that adequately simulate the level variations. The retention capacity RUMAX must be chosen in the range 0-20 mm, the aquifer recession time is large (more than 4 years), the storage coefficient (STOR) has a very large range but considering the aquifer formation it is unlikely to be less than 1% or more than 4%. The base level (BL), and the "equal runoff-percolation level" (RUIPER), and the half percolation time (THG) whose magnitude are a priori unknown may be calibrated to fit the selected values of RUMAX, STOR and TG. A very good calibration is obtained for the following values of the parameter: RUMAX = 20 mm, STOR = 1%, TG = 50 months. The fitted parameters are: RUIPER = 5.5 mm, THG = 5.9 months, BL = 26.5 m deep.

Fig. 3 shows that the whole period 1978-1985 is simulated accurately. The correlation coefficient is 0.977 and the average annual recharge is 29 mm.

SENSITIVITY ANALYSIS

It has been shown by Leijnse (1982) and Thiery (1989) that, after local linearization, it is possible to determine the confidence limits of the model parameters and also the confidence limits of the predictions of such a model. The responses of the model are locally linearized by the calculation of the derivative of the responses with respect to every parameter. These derivatives are called the influences of the parameters. Each

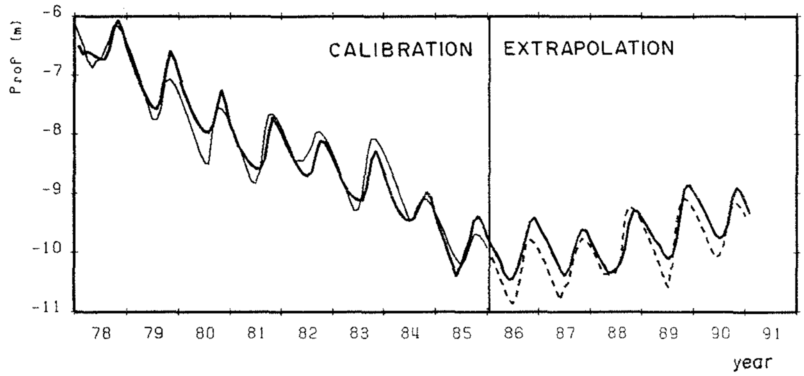

Fig. 3 Calibration of the model on water levels and extrapolation after 1985.

derivative is easily calculated from the difference between the reference simulation and a second simulation after a small modification of one parameter. The calculation is relatively straightforward, the only difficulty lying in the fact that the successive simulation deviations are not independent. This is solved by considering explicitly the autocorrelation of the deviations or by estimating an equivalent number of independent observations (Thiery 1990b). The confidence limits depend obviously on the quality of the fit and on the number of observations. A sensitivity analysis was first performed for the six parameters of the model. The correlation matrix of the influence of the parameters is given in Table 1.

Table 1 Correlation matrix of the influences of the parameters.

	RUMAX	RUIPER	THG	TG	STOR	BL
RUMAX	1					
RUIPER	0.68	1				
THG	-.047	-0.94	1			
TG	0.83	0.93	-0.86	1		
STOR	-0.59	0.99	0.99	-0.91	1	
BL	-	-	-	-	-	1

This matrix shows that difficulties may be anticipated because 6 coefficients out of 10 are larger (in magnitude) than 0.90. As a matter of fact the calculation of confidence limits is numerically impossible as the resulting matrix cannot be inverted (in computer single precision). A second calculation with five parameters (TG being fixed) leads to results which are unacceptable because the standard deviation of some parameters is so large that the linearization is no longer valid:

Parameter	RUMAX	RUIPER	THG	STOR	BL	A.r.
Nominal value	20	5.5	5.9	1%	-26.5	29
Standard deviation	3.2	40	43	7.3%	11.1	185

A. r. - annual recharge

To get acceptable results only the fitted parameters (RUIPER, THG, BL) have been analyzed, the others being considered as known values. The standard deviations of these parameters are :

Parameter:	RUIPER	THG	BL
Standard deviation:	1.3	1.5	0.99

and the correlation matrix of the parameters:

	RUIPER	THG
THG	0.94	
BL	-0.84	-0.62

The corresponding 95% confidence limits are displayed in Fig. 4.

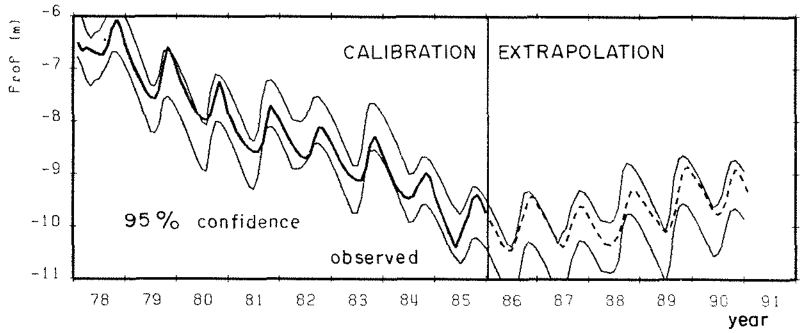

Fig. 4 Calculated 95% confidence limits of the water levels.

FUTURE EVOLUTION

In 1988 the model was used to predict the influence of higher precipitation. A simulation was made with 1978-1985 data, followed by a sequence of years identical to 1981 which corresponds to a median annual rainfall of the period 1959-1985. The results (Thiery, 1990a) showed that the level would rise slowly by one metre after five years and stabilize after more than 10 years.

EXTENSION OF DATA

In 1992, as the records for five following years became available, the model was run, with unchanged values of all parameters. It is shown in Fig. 3 that the calibration was reliable and robust because the simulated levels were very close to the observed ones though the hydrologic conditions changed a lot. The model could predict very accurately the inversion of the tendency and the rise in the levels due to the wetter period after 1985. It is interesting to notice that the prediction error is of the same magnitude during the calibration period and during the control period. Fig. 4 shows that the observed levels always stay inside the 95% confidence limits intervals which validates a posteriori the calculation of these confidence limits. The confidence limits due to the uncertainty of the parameters are shown in Fig. 5. It appears that the confidence interval is not constant and is larger during the second part of the record (after 1984). It is interesting to notice that, by chance, the evolution of the levels was very similar to the one predicted in 1988: a rise of 1 m after 5 years of median annual rainfall.

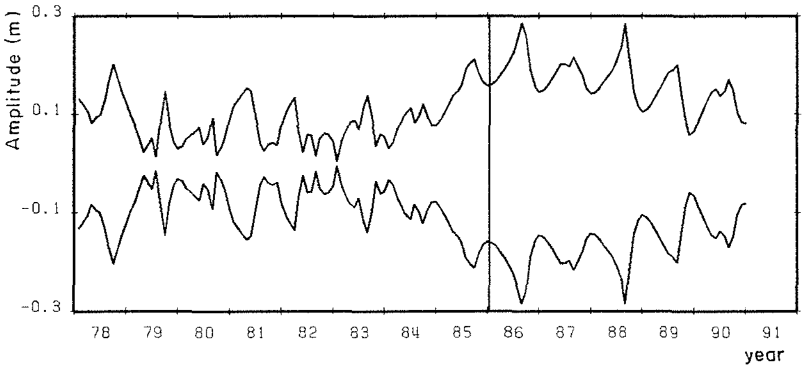

Fig. 5 Amplitude of the 95% confidence limits resulting from parameter uncertainty.

CONCLUSIONS

It has been shown that it is possible to use simple hydrological models to analyze natural aquifer level variations. However it is necessary to perform every time a sensitivity analysis to determine the reliability of the predictions of the model. Such sensitivity analysis can be implemented in any model, linear or not, through the calculation of the derivative of the response of the model with respect to the model parameters (around the optimal set of parameters). The case study of the ICHS observation well in Ouagadougou illustrates that GARDENIA model, though calibrated during a declining period was able to simulate a rise in the levels resulting from wetter years.

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