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DRAINAGE HYDROLOGY IN THE MARSHLANDS OF WESTERN FRANCE

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ABSTRACT

Flux prediction for drained fields can be obtained from convolution of a unit hydrograph with effective rain. The latter is calculated using a reservoir model, whose only parameter is the reduction coefficient of PET applied to gross rainfall. The transfer coefficient is calculated by two convolution methods, projection and multiple linear regression under constraints.

The model is applied to data obtained from drained plots in the marshlands of Western France, which are flat and lying at sea level. Since in wet winter periods natural drainage is insufficient for crop production, some farmers lower the water level by pumping.

In 5 plots ranging from 18 to 48 hectares, the evacuated flow was measured at the pump together with rainfall and PET. Results are used to fit the reservoir parameter of the model.

Although the model is purely stochastic, the results obtained can be interpreted in terms of the permeability of the plot and the type of drainage.

INTRODUCTION

Flux prediction is an important factor in drainage design. In the absence of flow generated by a watershed, the main parameter to be considered is local rainfall. The hydrodynamic properties of the soil and the characteristics of the drainage network must also be taken into account.

Several flux prediction models are available. In models based on the hydraulic properties of drained water tables (Kraijenhoff, 1958), the principal parameter is the height of the water table generating the simulated flux. This table is replenished by infiltration of rain water. Hydraulic conductivity and drainable porosity of the soil must also be taken into account. This method gives good results with homogeneous plots of a few hectares with well-known pedology (Lesaffre and Zimmer, 1987). If the experimental area is larger, the hydraulic properties of the soil are variable and the drainage network has an influence which is related to its size. In this case, deterministic models with rigid boundary conditions are less suitable, as Addiscot and Wagenet (1985) pointed out in a study on solute leaching models.

The proposed model is purely stochastic. The relationship between rainfall and discharge is calculated by two convolution methods, projection and linear regression under constraints. This method does not require analysis of infiltration and run-off on the plot. This type of model has been used in hydrologic studies (e.g. Newton and Winyard, 1967, Snyder and Amunsen, 1972). It does not rely on any hypothesis since it considers the

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system as a "black box". The relationship between rainfall and discharge provides useful information about the transfer mechanism, allowing it to be interpreted in physical terms. For example, a given relationship can be shown to be characteristic for certain soil types and drainage systems.

AREA DESCRIPTION

Our study was carried out in the marshlands of Western France which cover an area of about 210.000 hectares in the Atlantic seaboard south of Brittany and north of the Gironde estuary. This region has been formed by relatively recent deposits of fluvio-marine alluvia in existing bays. Several other areas in Europe were formed in the same way (e.g. the Guadalquivir marshes in Spain, the marshlands of the Tames estuary in Great Britain, the Dutch polders,the Nordfriesland marshlands in Germany). These regions are almost always flat and near sea-level.

Drainage of the French marshes began in the middle ages with a network of channels which carried excess water to the sea. Although this helped to control flooding, the watertable remained close to the surface in winter.

Farmers wishing to drain their land more effectively have thus to isolate themselves from the communal system. Water from these lands is collected in reservoirs which are emptied by pumping. The deeper water levels, thus obtained, allow the introduction of more intensive land drainage systems (beds or tile drains).

The climate of this region is oceanic, with average annual rainfall of 760 mm. Records over a period of thirty years show a water surplus (R>PET) of 300 mm from September to February and a deficit (R<PET) of 300 mm from March to August.

Drainability of these soils (60% clay content) depends on the structural stability and sodicity of the soil. Collas et al. (1985) distinguish three types of soils: A, B and C (Table 1).

In addition to rainfall and PET, daily recordings of discharge on five plots, in some cases over two drainage seasons, were available (Table 2). The discharges were calculated from the pumping times. Drain depth is approximately 1 m. In Plot 2, the difference in height between the top and the bottom of the bed is 0,90 m. Ditches in Plot 4 are 40 cms deep.

Table 1. Characteristics of the three types of marsh soil
ESP = Exchangeable Sodium Percentage

Soil type	stability	ESP 30-60 cm	hydraulic conductivity, m/day
A	stable	1	8
B	intermediate	14	3
C	unstable	28	1

Table 2. Network characteristics and experimental periods

N^0	Area, ha	Type of soil	Drainage	Spacing, m	Data
1	48	A	drains	19	Jan 79-Apr 79 Jan 80-Apr 80
2	24	A	beds	25	Feb 79-June79
3	18	B	drains	15	Jan 79-Apr 79 Jan 80-Apr 80
4	23	B	ditches	10	Feb 79-May 79
5	30	C	drains	15	Jan 79-June79 Jan 80-Apr 80

METHOD

It is assumed that discharge at time t, Q (t), measured at the exit of the drainage network of a plot, is equal to the weighted sum of the rainfall on the plot R(t-i) until time t-n; n is called "memory of the phenomenon".

This can be expresses as:

$$Q(t) = a_o R(t) + a_1 R(t-1) + \ldots + a_n R(t-n) \tag{1}$$

where a percentage a_o of the rain discharges immediately, a percentage a_1 of rain fallen at time t-1 discharges after one unit of time, etc.

The relationship between rainfall and discharge can also be expressed with continuous functions.

$$Q(t) = \int_0^t A(t-\tau)\, R(\tau)\, dt \tag{2}$$

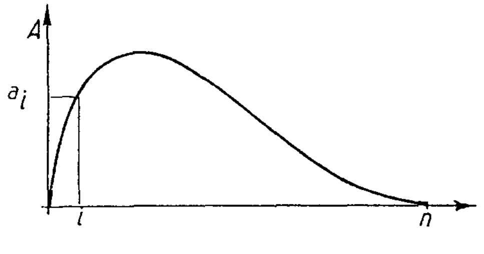

Fig. 1. Representation of the transfer function

The function $A(t-\tau)$ is called the impulse response of the system or transfer function. In hydrology, it is also known as the unit hydrograph (Sherman, 1935 in Linsley et al., 1978). The function $A(t)$ (Fig.1) is positive for all values of t. The memory of the phenomenon is now the length of time after which function A becomes virtually zero. Thus rainfall previous to t-n has no noticeable effect on discharge at time t.

If flux and rainfall are expressed in the same units (e.g. mm/day) the integral of the function A (t) for T varying between 0 and n is equal to the coefficient of restitution r. If the system is conservative (i.e. if R = Q, r = 1), all the effective rainfall reaches the exit.

The application of this function implies a linear relationship between discharge and rainfall. Rainfall on saturated soil generates discharge, but this is not so for precipitations on dry ground which are simply absorbed by the soil. To take account of this, we first calculate what is called "effective rainfall" using a simple model with one reservoir and one parameter. The soil is considered as a reservoir emptied by a part of the PET and filled by gross rainfall. Effective rain (R_e) is that part of gross rainfall which overflows from the reservoir (Fig. 2).

The only parameter to be fitted is the proportion k of the PET effectively evaporated. The transfer function is calculated from effective rainfall and discharge. Since evaporation is slight during the drainage seasons studied, it is assumed that there is always enough water available for evaporation. Thus, the volume of the reservoir may be considered as unlimited, and does not enter as a second parameter.

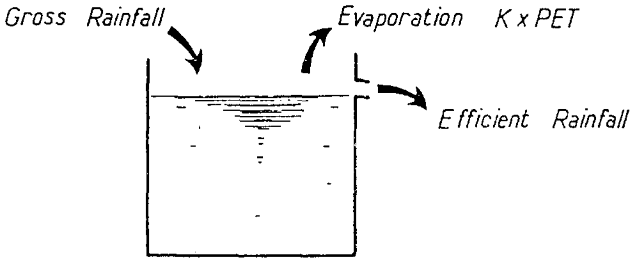

Fig. 2. Model for calculating effective rainfall from gross rainfall and PET

Calculation of the transfer function

The transfer function A is calculated from a series of discharge and effective rainfall readings. The following system has to be solved:

$$\begin{array}{c} Q_o \\ Q_1 \\ . \\ Q_m \end{array} = \begin{array}{cccc} R_o & R_1 & \dots & R_n \\ R_1 & R_2 & \dots & R_{n+1} \\ . & & & . \\ R_m & + R_{m+1} & \cdot\,\cdot & R_{n+m} \end{array} \quad \begin{array}{c} a_o \\ a_1 \\ . \\ a_n \end{array} + \begin{array}{c} \epsilon_o \\ \epsilon_1 \\ \\ \epsilon_n \end{array} \tag{4}$$

or briefly Q = R x A + E, while seeking to reduce $\sum_{i=1}^{n} \epsilon_i^2$ to a minimum

Of the various available methods, we chose deconvolution by projection and multiple linear regression under constraint. With deconvolution by projection (Emsellem and De Marsilly, 1971), the transfer factor A is obtained by successive projections on particular basic vectors. This is the same as refining A by progressively minimising the residues (calculated values minus measured values). This procedure presupposes the choice of time units n for the transfer function A which are whole powers of two (e.g. 4, 8 or 16 times the unit chosen).

In the case of linear regression, the estimator of A, $\dot{A}$ is obtained explicitly in function of the vector Q and the matrix R by the formula:

$$\dot{A} = ({}^{t}RR)^{-1}\ {}^{t}RQ \tag{5}$$

where t designates the transposition.

This method is unstable and does not necessarily give positive values for A. If the same constraints are imposed on multiple linear regression as on convolution by projection (i.e. suppression of the constant term and positivity of the coefficients using the algorithm described by Cazes (1978)), the transfer functions produced by both methods are identical.

RESULTS

For all plots the transfer function was calculated using one day as the time unit.

Example of simulation

Fig. 3 gives the result of fitting for Plot 1 in 1979. There is good correspondence between calculated and measured fluxes in rainy periods when discharges are greater than 2 mm per day. The very small discharges recorded in dry periods (e.g. between the 19th and 25th of February) were considered as having zero values.

Fitting the coefficient K

Coefficient K was fitted on the rainy period in the last ten days of April 1979, which was of particular interest since it followed a rainfree fortnight. During this period, average evaporation was 2.5 mm per day, equivalent to a deficit of 37.5 mm for the whole period. It is during such periods that the soil moisture reservoir most effectively acts as a buffer for evaporation. We give an example of restitution calculated by the model for three values of K:.6,.7 and .8. As shown in Fig. 4, the best fit was obtained with K = .7. This value tested in the same way on the other plots was used for all other calculations.

The validity of the model is checked by its stability over time. Fig. 5 gives the transfer functions A for each of the plots for which two years of readings were available. The average value for A for the whole period is also given.

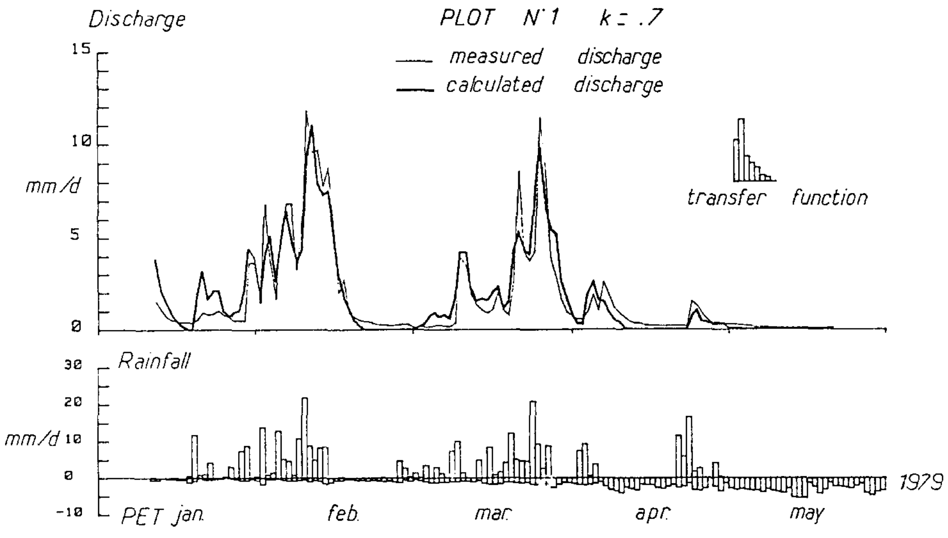

Fig. 3. Comparison of measured and calculated discharges on Plot 1 during 1979

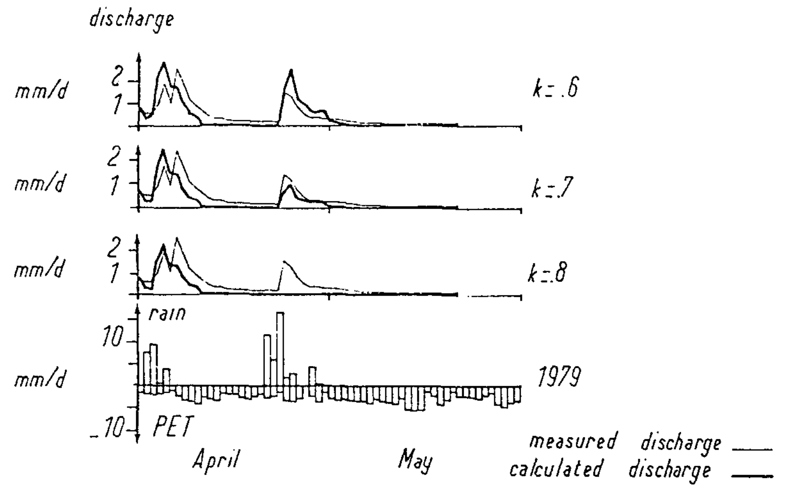

Fig. 4. Effect on calculated discharge of variations in coëfficient K

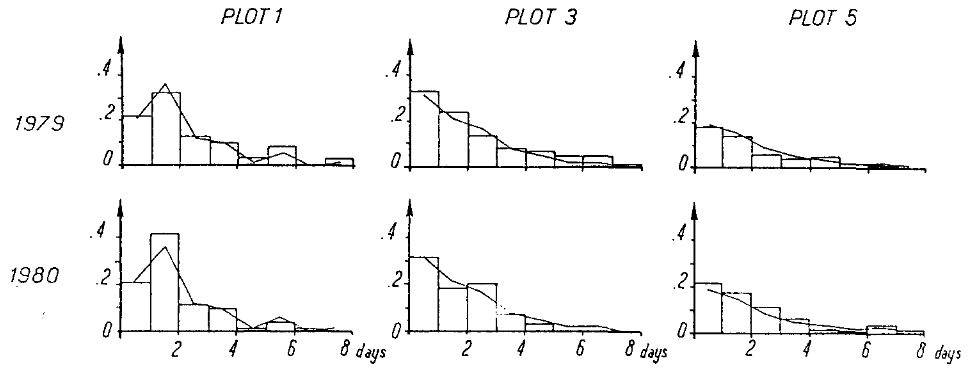

Fig. 5. Transfer function for three plots calculated for two successive years and comparison with the average transfer function

Fig. 5 shows that each plot has a particular transfer function and that for this plot the difference between the result for one year and the average for both years is slight. Transfer function A calculated for a period of one year, used in conjunction with coefficient K fitted at .7, can thus be considered as a characteristic of a system (e.g. a cultivated plot and its drainage network).

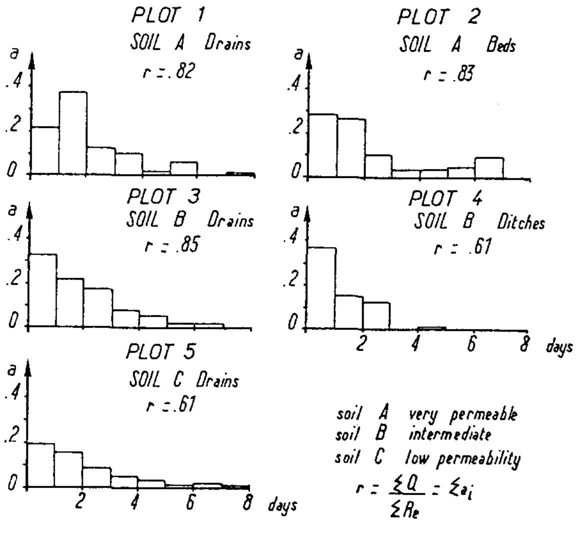

Fig. 6. Effect of soil type and drainage system.

Calculated transfer functions

All calculated transfer functions are shown in Fig. 6. Where readings for two years are available, an average is given. The restitution coefficient, equal to the sum of the components of the transfer functions, is also given.

The memory of the system is approximately seven days, except where drainage is by open ditches (Plot 4), when it is three days. Comparison between soil types (Plots 1, 3 and 5) shows that with the most permeable soil A (Plot 1) maximum response occurs the day after rain. On soils B and C (Plots 3 and 5), response decreases from the first day onwards. Drainage by beds of the most permeable soil A (Plot 2) produces a transfer function which shows some delay in response to rainfall. This function is very close to that for the plot withy subsurface drains for the same soil type (Plot 1). Restitution coefficients are greater than 0.8 except for Plots 4 and 5 which are characterised either by slowly permeable soil or by open ditch drainage.

DISCUSSION

The small number of cases studied does not allow extensive extrapolation of these results. However, taken in conjunction with the work of Damour (1981) on marsh soil or of Van Hoorn (1985) on clay soil, they show that the more impermeable the soil, the more rainfall evacuation takes place in the superficial part of the profiles. Thus a drained soil of type B and C (Plots 3 and 5) will behave similarly to a soil drained by an open ditch system. Conversely, in a very permeable soil with a deep water table, rainwater penetrating the soil will have a longer transit time. Restitutions are similar in this type of soil whether drainage is by subsurface drains (Plot 1) and beds (Plot 2). In permeable soil, the determining factor seems to be the depth of the draining mechanism.

CONCLUSION

The model suggested for flux prediction is based on a transfer function between flux and effective rainfall. The deconvolution methods suggested for calculating this function (also called unit hydrograph) are (i)projection and (ii)multiple linear regression under constraints. In spite of its simplicity, this stochastic method produces good predictions for fluxes greater than 2 mm per day. It is simple to operate and the parameters are easy to adjust without knowledge of the pedology or drainage system.

It has been shown, however, that the results of adjustments, particularly that of the transfer function, are quite typical for a given drained area and reflect its hydropedological characteristics.

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