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JANUSZ ŻELAZINSKI

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Application of the geomorphological instantaneous unit hydrograph theory to development of forecasting models in Poland*

JANUSZ ŻELAZIŃSKI
c/o Institute of Meteorology and Water Management, ul Podlesna 61, 01673 Warsaw, Poland

ABSTRACT Geomorphological instantaneous unit hydrograph (GIUH) theory has been applied for the estimation of the parameters of two conceptual models: a linear cascade model and a Laurenson-type model. Conceptual models, especially the linear cascade model, are more convenient for operational forecasting than the original GIUH model. A single linear reservoir model is suggested, with limited storage to represent the subsurface flow component. Subsurface flow is significant in Polish mountainous river catchments. Preliminary results of applying the model to operational flood forecasting are described.

L'application de la théorie de l'hydrogramme instantané unitaire géomorphologique pour la mise au point des modèles de prévision en Pologne
RESUME On a appliqué la théorie l'hydrogramme instantané unitaire (GIUH) pour l'estimation des paramètres des deux modèles conceptuels: le modèle des cascades linéaires des réservoirs et le modèle de Laurenson. Les modèles conceptuels (surtout le modèle des cascades des réservoirs linéaires) sont meilleurs pour les prévisions opérationnelles que les modèles originaux (GIUH). On a proposé un réservoir limité unitaire linéaire comme modèle du débit hypodermique. Le débit hypodermique est d'une importance capitale dans les bassins des rivières montagneuses en Pologne. On a décrit les résultats préliminaires de l'application de GIUH aux prévisions opérationelles des crues.

THE MODEL CONCEPT

The development of a coupled forecasting-decision model for flood protection and reservoir operation for the Upper Vistula basin system is now an important activity on which the Cracow Branch of the Institute of Meteorology and Water Management is engaged. The operational forecasting model, a component of the system, should satisfy the following conditions:

(a) Fast execution time and small operational memory (only a

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small minicomputer is available at the operational centre;

(b) Possibility of estimating model parameters from sparse observation data. The marked spatial variability of the input data implies the whole basin must be subdivided into many sub-basins which can be treated as lumped parameter systems. For these sub-basins adequate hydrological data do not exist.

The theory of the geomorphological instantaneous unit hydrograph (GIUH) developed by Rodriguez-Iturbe & Valdes (1979) and Rodriguez-Iturbe *et al.* (1979) seems a good tool for this task. However, for operational real-time forecasting the original GIUH theory had to be modified, as follows.

The original GIUH formulation is inconvenient for the updating procedure necessary in an operational model. At each forecasting time step, an initial state of the model must be updated. For this reason, a linear cascade model seems more convenient for the updating procedure because:

(a) it has a small number of state variables;

(b) the linear state space formulation of the model permits the application of an adaptive Kalman algorithm for updating.

GIUH theory has been applied to the estimation of the linear cascade parameters. Assuming that the gamma distribution probability density function describes the IUH, the formulae for t_p (time to peak) and q_p (peak discharge) derived in the GIUH method can be applied for the estimation of two gamma distribution parameters; in turn, the latter may serve for the estimation of the parameters of an equivalent linear cascade.

As a first step, we can calculate the β parameter in the gamma distribution (the number of degrees of freedom) as the solution of the equation:

$$(\beta - 1)^{\beta} \exp(1 - \beta) = 0.58\left(\frac{R_B}{R_A}\right)^{0.55} . R_L^{0.05} \tag{1}$$

where R_A, R_B and R_L are the standard Horton ratios. The right-hand side of equation (1) is a hydrological similarity coefficient, IR, introduced by Rodriguez-Iturbe *et al.* (1979). The number, N, of linear cascade reservoirs is rounded to an integer number using the parameter, β, calculated by equation (1). This round-up generates some deviation of the IUH peak with respect to the original GIUH theory. However, this deviation, as many simulations have shown, is generated by the rainfall excess estimation or by missing input data.

The time of storage, K (equal for each reservoir in the cascade), is calculated from:

$$K = \frac{1.58\ L\ R_B^{0.55}\ R_A^{-0.55}\ R_L^{-0.36}}{V_{max}(\beta - 1)} \tag{2}$$

where

K is time of storage (s);

L is length of the main stream in the basin (m); and

V_{max} is flow velocity (m^3s^{-1}) corresponding to the peak discharge, Q_{max} (m^3s^{-1}).

For the estimation of velocity in equation (2), some relation between V_{max} and Q_{max} is needed. The formula used herein is:

$$V_{max} = \begin{cases} \alpha\ Q_{max}^{\ \ n} & \text{for } Q_{max} \leqslant QB \\ \alpha\ QB^n & \text{for } Q_{max} > QB \end{cases} \tag{3}$$

where

Q_{max} is peak discharge in the stream cross section of the outfall of the basin (m^3s^{-1});

α, n are parameters derived from a set of discharge measurements or from regional formulae;

QB is bankful discharge.

The velocity, V_{max}, can be calculated in the following way. Our estimate must satisfy simultaneously two equations, viz. equation (3), and:

$$Q_{max} = \phi(V_{max}) \tag{4}$$

Equation (4) describes the relationship between V_{max} and Q_{max} only for a given event. We can evaluate a set of values which satisfy equation (4) only by numerical simulation for given net rainfall events, assuming a set of different values for V_{max}. The problem is to find among an infinite number of pairs of values that pair which satisfies equation (3).

To solve this problem the following algorithm is suggested. First, a lower bound for V_{max} is defined as:

$$V_{max_L} = Q_o^{\ n} \tag{5}$$

where Q_o < QB is a maximum value of the baseflow (in the simulation model) or the initial discharge (in the operational forecasting model).

V_{max_L} obtained in this way is substituted in equation (2) which gives a first estimate of the K parameter of a linear cascade. Next, the net rainfall-runoff simulation is performed, resulting in the next Q_{max_L} and V_{max_L} estimates.

In other words, the first simulation is obtained with the minimum possible value of V_{max}, and this gives the minimum possible value of the peak discharge, Q_{max_L}. (If $Q_{max_L} \geqslant QB$, the final estimation of V_{max} is given by equation (6).)

A second simulation is performed via:

$$V_{max_u} = \alpha\ QB^n \tag{6}$$

for the maximum possible value of V_{max} and this gives the maximum possible peak discharge, Q_{max_u}.

A first estimate of V_{max} is obtained as the point of intersection of the straight line:

$$\ln V_{max} = \ln\alpha + n \ln Q_{max} \tag{7}$$

and the straight line defined by two points with coordinates, $\ln Q_{max\,i}$, $\ln Q_{max\,i}$, resulting from simulations as described above. If this estimate satisfies equation (3) with a specified tolerance, i.e. ±0.01, computations are completed. If not, the procedure is repeated. In the next iteration, the first estimate of V_{max} is assumed as the new lower or upper bound. Usually two iterations are sufficient.

GIUH theory has also been applied to the estimation of parameters of a model of the Laurenson type (Laurenson, 1964). A stream of a specified order is represented by a single, nonlinear reservoir. The reservoirs are connected in the same order as the streams in the basin under study. A storage equation for an i-th order stream is:

$$S_i = k_i\, Q^{n_i} \tag{8}$$

where S_i is storage; Q_i is outflow; and k_i and n_i are parameters.

Departing from the basic assumptions of GIUH theory, the following formulae for the parameters in equation (8) can be derived:

$$k_i = \frac{\bar{L}_i}{\alpha_i} \tag{9}$$

$$n_i = 1 - m_i \tag{10}$$

Here $\bar{L}_i$ is the average length of an i-th order stream, and α_i, m_i are parameters of an equation:

$$v_i = \alpha_i\, Q_i^{m_i} \tag{11}$$

where v_i is a mean flow velocity. This model, in addition to taking advantage of the linear cascade, enables us to reproduce the spatial distribution of an input over the streams in a basin, and to account for variable flow velocities in the streams of a given order.

The last modification introduced in the original GIUH theory is the introduction of an interflow (subsurface flow) component. In Poland, most of the runoff of moderate floods occurs in the form of interflow. This flow component is much faster than groundwater flow. However, the residence time of water flowing in the soil mantle cannot be neglected. A retardation mechanism for the soil mantle is represented by a single linear reservoir with limited storage:

$$S = \begin{cases} KSQ \text{ if } KSQ \leqslant S_{max} \\ S_{max} \text{ if } KSQ > S_{max} \end{cases} \tag{12}$$

Here KS and S_{max} are respectively the time of storage and maximal storage capacity of the soil mantle in which an interflow occurs. As one effect of the model described, surface flow (with zero residence time in a soil) occurs only in the cases when the rainfall intensity is greater than $-S_{max}/KS$, i.e. the maximum subsurface flow rate. Moderate storms generate only subsurface flow, which is in agreement with observations.

In the stochastic framework assumed by Rodriguez-Iturbe *et al.* (1979), the constrained linear reservoir which describes a soil retardation mechanism can be interpreted as follows. The residence time of a drop of effective rain in a soil has a discrete/continuous distribution. The discrete part of the distribution is connected with zero residence time and modelling surface flow. The continuous part of the distribution (for subsurface flow) is exponentially distributed.

Probably relationships exist between KS and S_{max} and some parameters which can be evaluated from topographic and geological maps. S_{max} is proportional to soil depth and porosity. KS is a function of the path length of a raindrop within the soil mantle and of the flow velocity. Average length can be deduced from the river network density. Velocity is a function of hill slope and flow resistance generated by soil and depending on soil structure. Attempts are being made to establish adequate relationships.

CONCLUDING REMARKS

Operational forecasting models of the rainfall-runoff class based on the concept discussed are at present being tested. The models are to be implemented for the Carpathian River catchments of the Upper Vistula basin, with the catchment areas ranging from 300 to 5000 km^2.

So far, the results are encouraging. Between the two models discussed the linear model seems preferable because of faster computation and easier updating. Although a nonlinear model accounts for the space variability of the input, the same results may be obtained by dividing the catchment into subcatchments represented by linear, lumped parameter systems. In this case computer execution time is much shorter. It should be stressed that an acceptable agreement between simulated and observed hydrographs has been obtained only after introduction of the interflow component. Two parameters of the interflow storage model can be easily estimated based on two or three observed rainstorm hydrographs. The interflow parameters do not vary much in space.

For these reasons the model discussed can be calibrated for catchments with few runoff observations. The only condition in such cases is to have at one's disposal a topographic map of a scale enabling an estimation of the geomorphological parameters to be made and to make a regional study beforehand.

This conclusion has been proven for the Upper Dunajec catchment where the regional formulae for estimation of the parameters α_i and m_i in equation (11) had been established and little space variation of the parameters KS and S_{max} in equation (12) had been noted. For this study the hydrometric data from 14 river gauges were used. In other words, the parameters of the model discussed appear to be well suited for a generalization and a space extrapolation.

It seems that in this way, a good solution of important practical problems has been obtained, namely the spatial decomposition of a big catchment into subcatchments of uniform rainfall and flood formation conditions.

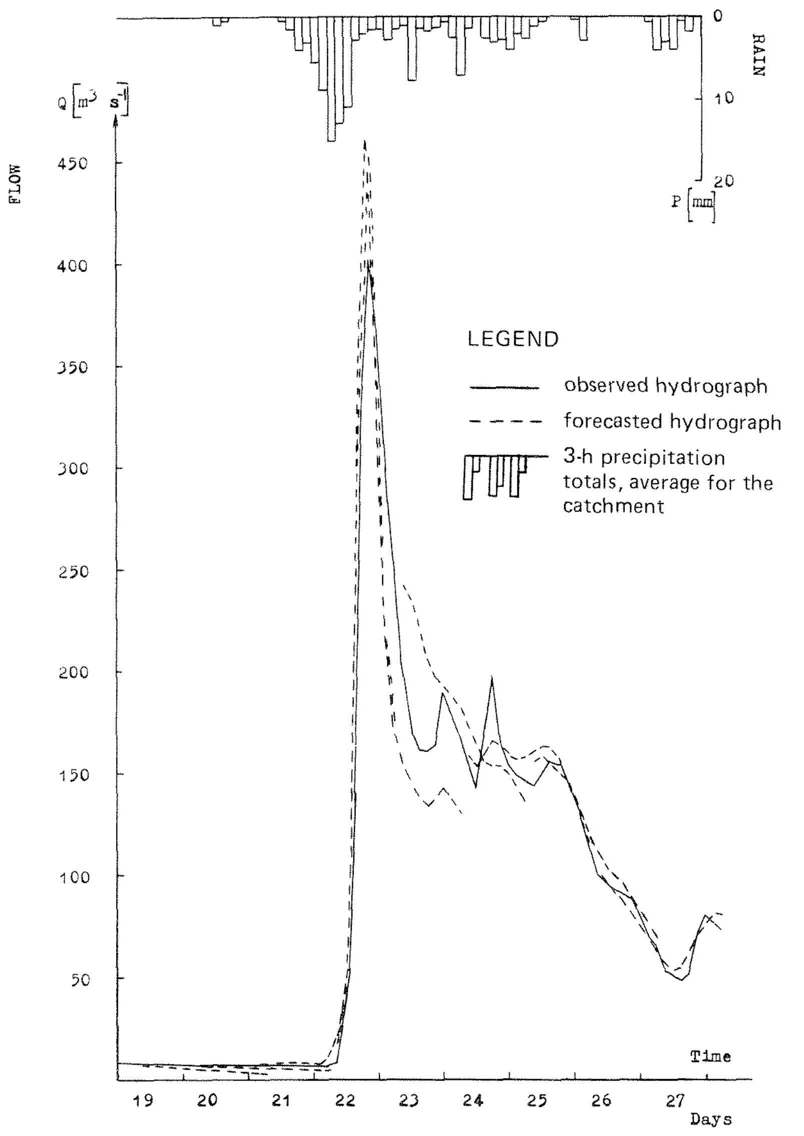

Fig. 1 The flow hydrograph of the Skawa River for the flood event during 19–27 July 1980. The 48-h flow forecasts computed by the linear cascade model parameters which are estimated using the GIUH theory. Forecast precipitation is assumed to be the same as the observed values.

It should be noted that a model described as linear is really linear only for a given event (or given forecast). For several events the model is, of course, nonlinear because the time constant, K, is a function of flow velocity, V_{max}, which in turn depends on peak discharge, Q_{max}.

An important role in the models described arises from an evaluation of the rainfall excess. In our case the rainfall excess can be defined as that part of total rain which generates fast forms of outflow i.e. surface and subsurface flow. In our study, many models of rainfall excess separation were tested, starting from very simple two-parameter relationships similar to Horton's formula up to a sophisticated 12-parameter conceptual model. Each model gave similar results from the point of view of errors.

The parameters of each model vary in time (from event to event and in the sequence of time steps of the calculations). Finally, we have chosen simple models convenient for updating procedures. In the operational version of their forecasting models the modified SCS formulae (US Dept of the Interior, 1965) is being used.

An example of the model performance on the data of the Skawa River, a tributary of the Upper Vistula, is shown in Fig.1. The catchment area is 835 km^2. The forecasts are repeated every 24 h and the forecast lead time is 48 h. The parameters of the linear cascade and subsurface flow models were relatively stable from storm to storm. However, the parameter S in the SCS formulae used for the rainfall excess determination is variable in time. In the operational version of the forecasting model, an updating procedure for the S parameter has been introduced by fitting the latest simulation to observed data. It was assumed that S depends on API and a regression relationship was established and introduced into the model.

For the identification of the model parameters only Horton's geomorphological ratios derived from the topographic map and the set of results of discharge measurements at the outfall cross section of the basin are used. The KS and S_{max} parameters for the Skawa are assumed to be equal to those identified for the neighbouring Dunajec River basin. It seems that the model parameters obtained in such a way are better if physically based than those estimated through optimization.

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