Estimation of High Floods by Three Rainfall-Runoff Models with Short Rainfall-Runoff Series (Alzette River Basin, Luxembourg)

El Idrissi, A.[1] **Drogue, G.**[1,2], **Pfister, L.**[1], **Iffly, J. F.**[1], **Hoffmann, L.**[1], **Hingray, B.**[3], **Guex, F.**[3]

[1] *CREBS-Cellule de Recherche en Environnement et Biotechnologies, Centre de Recherche Public – Gabriel Lippmann, 162a, Avenue de la Faïencerie, L-1511 Luxembourg, Grand-duchy of Luxembourg.*
[2] *Centre d'Ecologie Végétale et d'Hydrologie, UMR-MA 102 ENGEES-ULP, 1, quai Koch, F-67070 Strasbourg cedex, France.*
[3] *Ecole Polytechnique Fédérale, IATE - HYDRAM, CH-1015 Lausanne, Switzerland.*
(idrissi@crpgl.lu)

Abstract: This paper presents a comparison of hourly high runoff simulations using short discharge series for three parsimonious rainfall-runoff models that differ substantially in their conceptualisation (two reservoir models and one physically-based model). The models were applied to eight monitored sub-basins characterised by different physiographical properties and hydrological behaviour, located in the experimental Alzette river basin (Luxembourg). The model calibration procedure consists in selecting only rainfall-runoff events with highest peak flows and highest runoff production that occurred during the available measurement period (1997-2001). Simulated extreme values of peak flow and stormflow volumes were analysed and compared to observed runoff series. Results show that the models are able to provide good fits to the rainfall-runoff event's hydrographs. Nevertheless, the physically-based MHM model gives the best results in terms of predictive accuracy.

Keywords: rainfall-runoff; modelling peak flows; stormflow volume; Alzette river basin; Luxembourg.

1. INTRODUCTION

Rainfall-runoff models are important tools in operational hydrology and can differ in terms of mathematical representation of processes, spatial discretisation of the basin and data requirements. In practice, the superiority of distributed physically based models over simpler models for operational purposes is currently an open question. This question is important for users of models, who may need to judge whether the increased costs of obtaining and processing spatially-distributed basin data can be justified in terms of increased reliability of model predictions [Donnelly-Makowecki and Moore, 1999]. Therefore, a comparison of models is required to provide a basis for choosing a model that will yield an adequate performance in a specific application for the lowest cost.

The purpose of this paper is to compare the outputs of three rainfall-runoff models using short observation data series.

2. METHODS

2.1 Study area and data

The three models were applied to eight sub-basins (Figure 1, Table 1), located in the experimental Alzette basin (1176 km^2, Grand-duchy of Luxembourg). The selected sub-basins were chosen to be representative of the variability of basin sizes, geological conditions, physiographical properties, as well as the availability and quality of streamflow data (Table 1).

Three sub-basins are homogeneous from a lithological point of view with essentially marls (Mierbech, Mess, Eisch). Except for the Alzette in Pfaffenthal, all other sub-basins can be considered as rural and forested. Note that former mining activities in the right bank tributaries disturb the hydrological behaviour of the Alzette in Pfaffenthal.

Basin	Outlet	Area (km^2)	Impervious formations (%)	Pervious formations (%)	Cultivated land (%)	Grassland (%)	Forested land (%)	Urbanised land (%)
Mierbech	Huncherange	7.3	95.2	4.8	45.9	15.8	32	6.2
Pall	Niederpallen	34.6	66.8	33.2	19.1	51.6	25	3.9
Mess	Pontpierre	36.1	91.6	8.4	21.1	59.1	8.7	11.1
Roudbach	Platen	47.1	59.1	40.9	32.4	25.8	36.7	4.8
Eisch	Hagen	47.2	58.4	41.6	30	50.6	10.5	8.9
Mamer	Schoenfels	84.7	51.9	48.1	22.7	33.9	31.6	11.6
Attert	Reichlange	166	83.4	16.6	23.3	37.6	34.9	4
Alzette	Pfaffenthal	349	65.7	34.3	25.4	26.8	25.2	19.2

Impervious formations: Impermeable geology is substratum with dominance of marls, schists, clay or silt
Pervious formations: Permeable geology is substratum with dominance of sandstone

Table 1. Physiographical characteristics of the selected sub-basins

A dense hydrological observation network has been set up in the experimental Alzette basin since 1995. 16 streamgauges are recording water levels at a 15-minute time step.

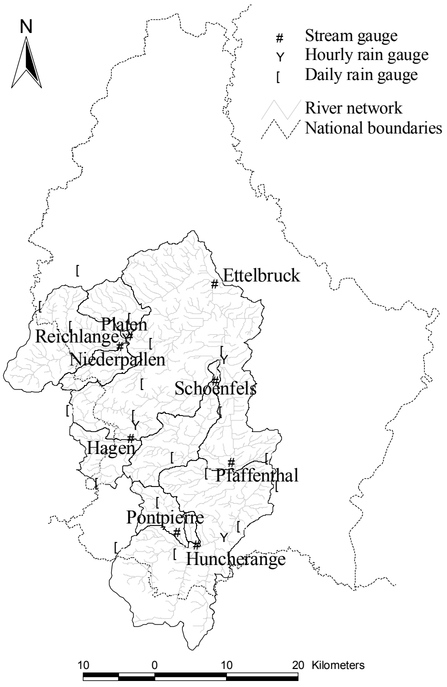

Figure 1. Study area and measurement networks

Total rainfall (Pt) was collected via 19 non-recording daily raingauges and 4 raingauges recording at an hourly time-step, covering the study areas and available for the modelling period. To compute hourly rainfall for each sub-basin, the daily areal rainfall (interpolated via Thiessen polygons) was time disaggregated according to the temporal structure of rainfall of the 5 hourly reference raingauges.

Potential evapotranspiration (PET) was estimated using the Penman-Monteith formula [Monteith and Unsworth, 1990] with daily meteorological data measured at the Luxembourg airport. The same climatological data series were uniformly applied to the whole study area.

Data sets used in this study come from the hydro-climatological database built-up and validated by the CRP-GL (CREBS laboratory).

2.2 Hydrological model description

Three parsimonious rainfall-runoff models, simulating hourly mean discharge were tested. They differ substantially in their runoff production and routing functions (Table 2).

The Hydrological Recursive Model, HRM, [Leviandier et al., 1994] is called recursive because the reservoir structure at order n is obtained from reservoir structure at order n-1 by a simple transformation (namely, routing + lateral input). In the following, the HRM model was applied in its semi-distributed version, which accounts for the permeability of lithological formations. In this case, six free parameters must be optimised by the Rosenbrock method.

The lumped SOCONT model [Guex, 2001] has three parameters to be fitted. The SOCONT parameters have no physical meaning even though significant relationships with specific basin characteristics could be found.

The third model, the Meshed Hydrological Model, MHM [Batardy, 1984] is a storm runoff event model. For running this model, physical characteristics of the basins (Table 2) were spatially distributed into regular squared grid cells by using a Geographical Information System; the grid size used for this study is 100 m.

In view of rainfall-runoff modelling, total discharge (Qt) is separated via the Base Flow Index (BFI) software [Kaden, 1994] into two components representing the storm runoff (Qr) and

	MHM	HRM	SOCONT
Type of the model	Distributed	Semi-distributed	Lumped deterministic
Production function	Runoff coefficient (constant)	Soil reservoir	Soil reservoir
Routing function	Iso-chronal map	Geometrical isochrones	Drainage reservoir
Base flow	Not considered	Drainage reservoir	Drainage reservoir
Calibration procedure	Trial-error (manual)	Automatic	Two steps (automatic)
Calibration criterion	Nash-Sutcliffe coefficient	1-Nash-Sutcliffe coef.	Nash-Sutcliffe coef.
Hydroclimatic inputs	Pt, Qt, Qr, Qb	Pt, PET	Pt, PET
Geographical inputs	Grided maps: geology, river network, slope, flow directions	Geology, drainage area, isochronal zones	Drainage area
Outputs	Qr, isochronal map	Qt	Qt, Qb, PET
Parameters meaning	Physical meaning	Physical meaning	No physical meaning

Table 2. Main characteristics of the three tested models for this case study

the base flow (Qb). To produce stormflow (Qr), the MHM uses two matrices combining two geological classes and three slope classes: the first matrix contains the stormflow coefficients (2x3=6 parameters) and the second one contains the runoff velocities (2x3=6 parameters). To obtain the total discharge, the Qr values are added to the estimated Qb. MHM model calibration consists in fitting manually the 12 parameters values [El Idrissi et al., 1999].

2.3 Modelling calibration procedure

The available streamflow measurement period extends over 4.5 years from January 1997 to March 2001; since the number of high flood events is limited, the series are not long enough to perform a statistical analysis of high floods. However, it is possible to calibrate the model parameters by extracting medium and high flood events from the available data series.

In the first step, only hydrographs with the highest peak flows are retained; a threshold is arbitrarily selected for a given sub-basin (Figure 2).

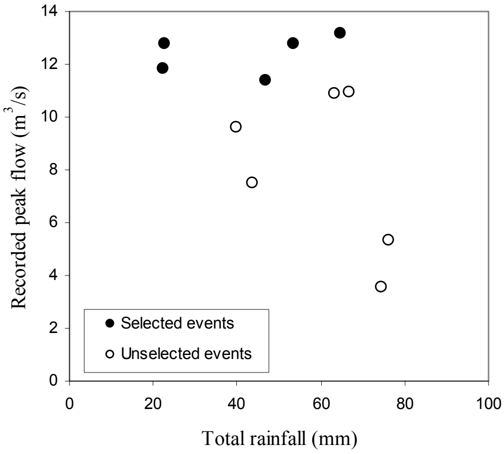

Figure 2. Selection of events according to the peak flow criterion (Mamer at Schoenfels)

Next, events that have the lowest runoff production volumes are rejected (Figure 3). The rainfall-runoff events finally retained (no more than 4 to 5 per sub-basin) present similar saturated soil moisture conditions.

In the second step, the model parameters were optimised according to three different methods: i) all rainfall-runoff events were aggregated into a unique sequence preceded by a one month period for initialising storage reservoirs; ii) each event was separately calibrated with an initial warm-up period for base flow. Optimal model parameters were averaged; iii) using the continuous data series (usual application of the SOCONT and the HRM models). The 3 methods give results with slight differences and will be thus considered as comparable.

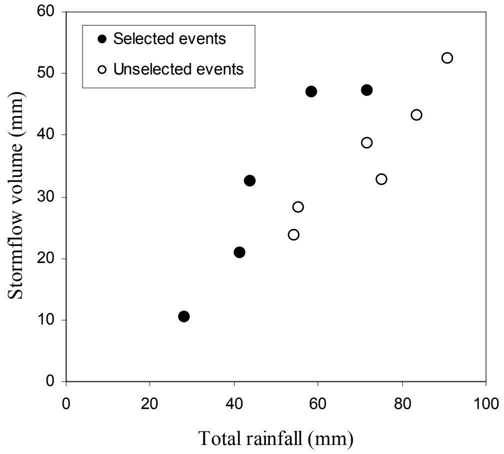

Figure 3. Selection of events according to the stormflow volume criterion (Eisch at Hagen)

2.4 Criteria for model performance

Both numerical and graphical criteria were considered to provide a good overall indication of the model's capabilities. The accuracy criteria concern the stormflow shape (Qr), peak flows and stormflow volumes.

For assessing hourly global model efficiency, the Nash and Sutcliffe [1970] coefficient was computed for each sub-basin:

$$\mathrm{CNS} = 1 - \frac{\sum_{i=1}^{n}\left(\mathrm{Qsim}_i - \mathrm{Qobs}_i\right)^2}{\sum_{i=1}^{n}\left(\mathrm{Qobs}_i - \overline{\mathrm{Qobs}}\right)^2} \qquad (1)$$

where n is the number of discharge values of the selected events hydrographs, Qsim_i and Qobs_i are the simulated and the observed stormflow values respectively, and $\overline{\mathrm{Qobs}}$ is the average of observed stormflow values. CNS is less than 1 (equal to 1 when Qsim = Qobs).

To assess goodness of fit and accuracy of simulated peak flows and stormflow volumes, mean absolute error (MAE), expressed in percentage was determined for each sub-basin :

$$\mathrm{MAE}\,(\%) = \frac{1}{n}\sum_{i=1}^{n}\left|\left(\mathrm{Ysim}_i - \mathrm{Yobs}_i\right)/\mathrm{Yobs}_i\right| \qquad (2)$$

where n is the number of discharge values of the selected events hydrographs, Ysim_i stands for the computed values and Yobs_i stands for the measured values. The nearer the MAE is to zero the better the method.

To quantify the importance of the difference between observed and simulated stormflow volume, bias or magnitude of mean errors (MBE), expressed in mm, was determined for each sub-basin :

$$\mathrm{MBE} = \frac{1}{n}\sum_{i=1}^{n}\left(\mathrm{Ysim}_i - \mathrm{Yobs}_i\right) \qquad (3)$$

3. RESULTS

3.1 Model efficiency

The CNS variation for the tested sub-basins is depicted in Figure 4. In terms of general performance, the MHM model gives slightly better results than SOCONT and HRM. The average CNS is of 0.76, 0.73 and 0.72 respectively. However, MHM seems to be less efficient on the largest sub-basins (Attert at Reichlange and Alzette at Pfaffenthal). The three models obtain their worst CNS for the Mess sub-basin. It is possible that the influence of a highway on the natural hydrological behaviour of this homogeneous sub-basin does not permit an accurate simulation of observed hydrographs.

The most homogeneous and the less homogeneous tested sub-basins (Mierbech and Alzette in Pfaffenthal) have an unexpected significant influence on model performance. The best results are obtained for the less homogeneous one. This could be explained by Mosley [1981]: ‘where a number of hydrological factors are equally important in controlling hydrologic regime, and where the heterogeneity differs from one property to another, a complex mosaic of hydrologically apparent homogeneous areas may result.

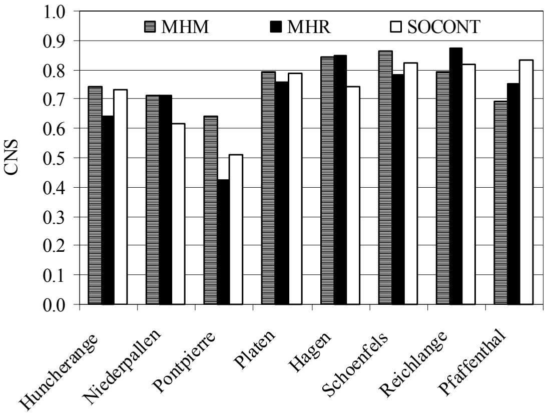

Figure 4. Comparison of model efficiency (Nash and Sutcliffe coeffcient)

The MAE and MBE criteria are used to characterise the stormflow volume (SFV) variations for the eight chosen sub-basins. The comparison of the results provided by the three models concerning SFV is shown in Figure 5.

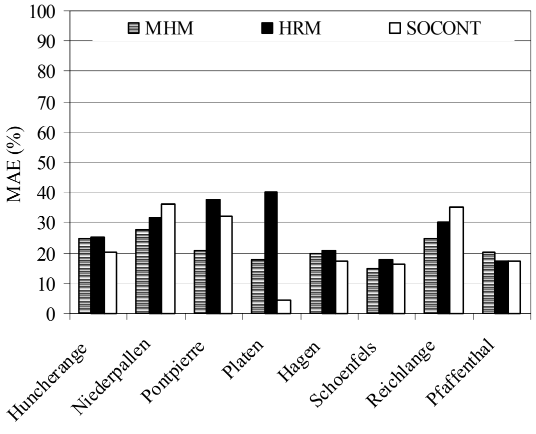

Figure 5. MAE criterion for simulated stormflow volumes

Averaged MAE values obtained by MHM and SOCONT are close and thus comparable (21.4 and 22.5 respectively). Excepted for the contrasted result recorded for the Roudbach at Platen sub-basin, no specific tendency is observed for the remaining sub-basins.

The MHM and SOCONT models have slightly positive (3.5 mm) and negative bias averages (-4.6 mm), respectively. However, HRM largely underestimates the volume (-14.2 mm), especially for the smaller sub-basins (Figure 6).

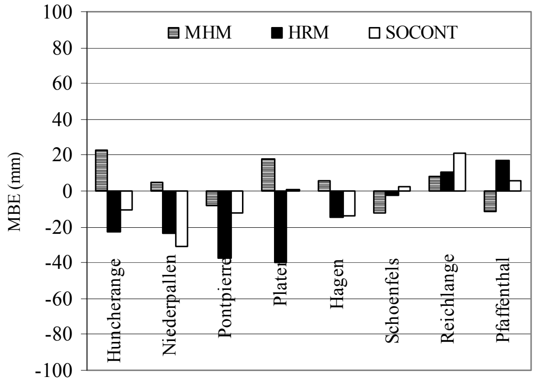

Figure 6. Bias recorded by the three models (MBE criterion)

For the storm peak flow (SPF) values, MHM gives better results than the two other models and the difference is rather significant (Figure 7). Note that the simulated peak flow values were extracted in a window of ± 3 hours around the observed peak flow values.

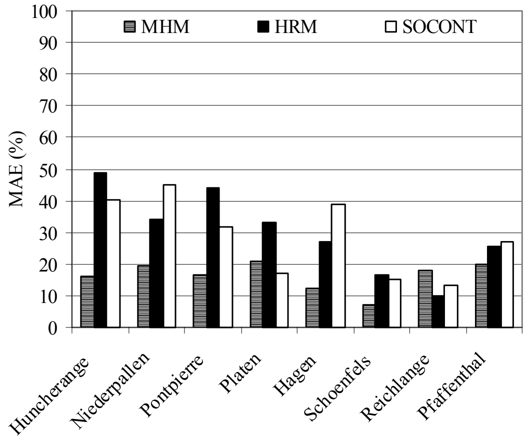

Figure 7. Comparison of simulated peak flow (MAE criterion)

The MHM leads to a MAE of 16.3% on average. This value reaches 29.9% and 28.5% for HRM and SOCONT, respectively. The same, but less pronounced tendency is found for the MBE criterion. The manually 'oriented' calibration method and the simulation of only net runoff can partially explain the observed differences. But the better results recorded for the CNS and the SFV confirm the overall better accuracy of MHM.

The best averaging MAE results of SFV simulations are obtained on the Mamer (13.1%) and Attert (13.8%) sub-basins. These are medium sized sub-basins with a relatively homogeneous spatial distribution of geological formations: in the upstream-downstream sense for the Mamer and north-south sense for the Attert.

As the number of sampled rainfall-runoff events does not exceed 5 for each chosen sub-basin it is inadequate to use them to carry out any trend concerning the very high peak flows and volumes.

In Figure 8 (page down) are represented for the three models, scatter plots of observed and simulated storm peak flows of all selected sub-basins. Observed peak flow values ranging from 35 m^3/s to 50 m^3/s are lacking.

The SOCONT model shows a systematic under-estimation for the entire range of peak flows (Figure 8). HRM simulates well low observed peak flow values and slightly overestimates measured peak flow values superior to 40 m^3/s (Figure 8). Model predictions towards extreme values might be exaggerated. On the contrary, the SOCONT model will systematically under-estimated extreme values (Figure 8). MHM model results suggest a slight trend towards an under-estimation of peak flows superior to 25 m^3/s.

In terms of stormflow volume (Figure 9), both HRM and SOCONT show progressive under-estimation of volume from low to high values. However, MHM gives a good trend estimation of observed volume discharge and provides a better tendency for volumes of extreme events.

4. CONCLUSIONS AND PERSPECTIVES

A procedure to analyse and compare hourly high floods simulated by three rainfall-runoff models with short rainfall-runoff series is presented.

The results based on the CNS criterion show that the three tested models are well suited to assess the simulation of high event's discharges for the eight selected sub-basins in terms of general shape of the observed storm hydrographs. The results based on the MAE and MBE criteria suggest that the MHM model is best suited for identifying the peak flows and stormflow volumes within the study area, regardless of the sub-basin's scale and characteristics. The SOCONT model shows a systematic under-estimation of both peak flow and stormflow volumes and should not be used for extreme values.

The accuracy of the calibration procedure would be better if sufficient higher rainfall-runoff observed events would exist. In the future, each sub-basin will be separately examined. Concerning the method verification, the lack of hourly Intensity-Duration-Frequency curves in the Alzette basin does not allow the use of a range of designed storm events with adequate return periods.

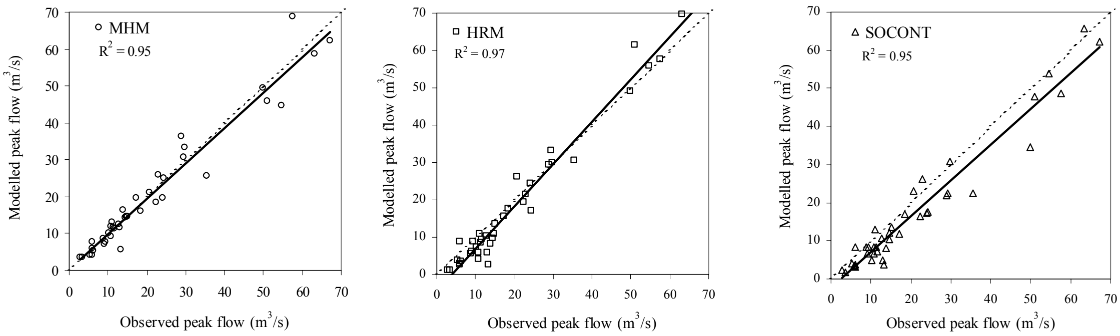

Figure 8: Comparison of observed and simulated peak flow

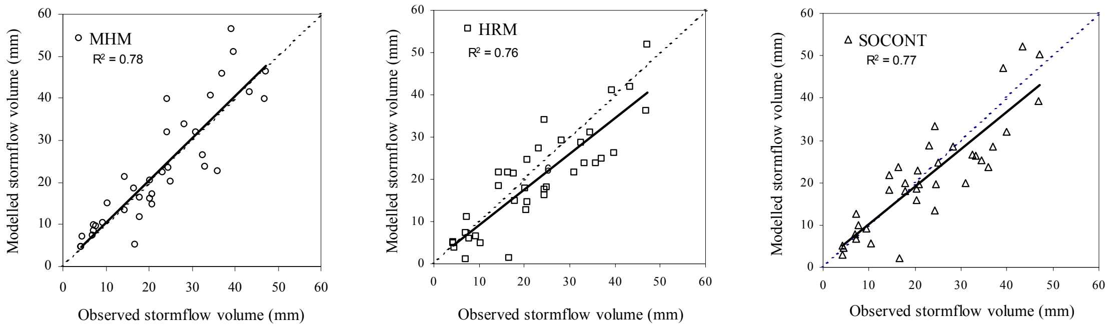

Figure 8: Comparison of observed and simulated stormflow

Acknowledgement

Thanks to Leviandier T. for providing the HRM model and for his comments.

5. REFERENCES

Batardy, J., L'élaboration d'un modèle hydrologique conceptuel maillé pour la prévision des débits en temps réel. Application au bassin versant de la Lesse à Daverdisse. *Rapport final, S.A. LGR N.V., Athus*, 254 pp., Belgique, 1984.

Donnelly-Makowecki, L.M., and R.D. Moore, Hierarchical testing of three rainfall-runoff models in small forested catchments, *Journal of Hydrology*, *219*, 136-152, 1999.

El Idrissi, A., I. Ruthy, P. Hang, M. VanClooster, E. Persoons, Regionalization of rainfall-runoff parameters in the catchment of the Dyle (Belgium), Act of: International conference on Modelling of transport process in soils at various scales in time and space, Edited by J., Feyen & K. Wiyo, Leuven, Belgium, November 24-26, 1999.

Guex, F., Modélisation hydrologique dans le bassin versant de l'Alzette (Luxembourg), régionalisation des paramètres d'un modèle global, Travail pratique de Diplôme, Ecole Polytechnique Fédérale de Lausanne, 67 p., 2001.

Kaden, U., Etude de la séparation des écoulements sur différents bassins d'Alsace. Application et automatisation de la technique du Base Flow Index (BFI), Master thesis, Université Louis Pasteur, Strasbourg, 55 pp., 1994.

Leviandier, T., G. Mantilla-Moralles, A. Zermani, Etude comparative de la résolution spatiale des modèles hydrologiques sur le bassin de la Charente. *Symposium sur les relations continent-zones côtières, GIP Hydrosystèmes*, La Rochelle, 17 pp., 1994.

Monteith, J. L. and M. Unsworth, *Principles of Environmental Physics*, 2nd ed., Edward Arnold, London, 1990.

Mosley, M.P., Delimitation of New Zealand hydrologic regions, *Journal of Hydrology, 49*, 173-192, 1981.

Nash, J.E., and J.V. Sutcliffe, River flow forecasting through conceptual models. Part I: a discussion of principles, *Journal of Hydrology*, *10*, 282-290, 1970.