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Simulation of streamflow by a regionalized lumped rainfall–runoff model over Luxembourg

B. HINGRAY[1], F. GUEX[1], D. GUEX[1], S. PUGIN[1], A. MUSY[1], L. PFISTER[2], A. IDRISSI[2], J. F. IFFLY[2] & L. HOFFMANN[2]

1 *Hydrology and Land Improvement Laboratory, Swiss Federal Institute of Technology (EPFL) CH 1015 Lausanne, Switzerland*
benoit.hingray@epfl.ch

2 *CREBS-Cellule de Recherche en Environnement et Biotechnologies, Centre de Recherche Public – Gabriel Lippmann, 162a Avenue de la Faïencerie, L-1511 Luxembourg, Luxembourg*

Abstract A parsimonious hydrological model was applied to simulate continuous discharge series on 17 gauged sub-catchments of the Alzette Basin in Luxembourg. The model has only three calibration parameters: the two first Model Parameters (MPs) are involved in the flow production process and in the baseflow reconstitution, while the third governs the quick flow component. The calibrated MP values obtained for nine calibration catchments were regionalized for the Alzette physiographic and hydrological area and regional equations were derived from a stepwise regression analysis linking these MP values to different Catchment Physical Characteristics (CPCs). To allow for a robust regionalized model, a manual two-step and bi-signal calibration procedure was applied to determine the optimal MP for each calibration catchment. The regionalization was next improved using the observed correlation between two parameters. The regional equations obtained produce both hydrological meaning and statistical significance. The regionalized model was evaluated on the eight gauged catchments that were not used for the development of the relationships between MPs and CPCs.

Key words flow simulation; parameter regionalization; rainfall–runoff; reservoir based model

INTRODUCTION

Long-term discharge series allow the derivation of relevant hydrological information such as flow duration curves or discharges quantiles. For ungauged catchments, such series can be reconstructed via continuous simulation thanks to regionalized hydrological models. The possibility of estimating the model parameters on the basis of external information obtained, for example, from gauged catchments is a significant hydrological issue (e.g. Abdulla & Lettenmaier (1997), Sefton & Howarth (1998) and Perrin (2000)). Regionalization works are mostly based on regression relationships developed between model parameters (MPs) and catchment physical characteristics (CPCs). These approaches may be severely limited, particularly as a result of too high a number of parameters or of the strong correlation that may exist between some of them.

The regionalization work presented here was carried out with a parsimonious conceptual hydrological model for 17 catchments of different sizes (18 km^2 to 1176 km^2) and geological substrates. These catchments are part of the Alzette basin, located in Luxembourg, and thus belong to a small and fairly homogenous region from a climatic, hydrological and physiographical point of view (Pfister *et al.*, 2000). The work was undertaken as part as the Pan-European FRHYMAP (Flood Risk scenario and Hydrological Mapping) project (Hoffmann, 2001).

Data

The Alzette basin is mainly situated in the Grand-Duchy of Luxembourg (Fig. 1). Data (time series as well as physiographic data) come from the hydro-climatological database built and validated by the Gabriel Lippmann Public Research Center in Luxembourg.

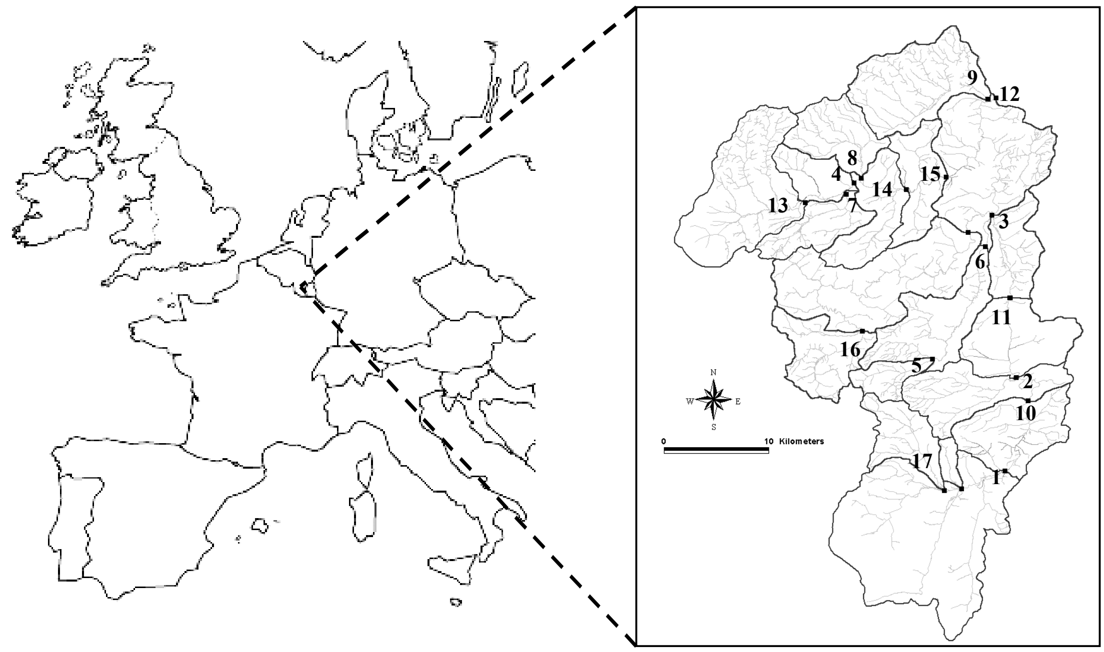

Fig. 1 Experimental catchments and gauging stations of the Alzette basin (Alzette outlet is 12.)

The area of the catchments ranges from 18 to 1175 km^2; the largest catchment includes all other catchments. The elevation of the catchments is quite homogenous as the average elevation ranges from 295 to 390 m a.m.s.l. The development of regional equations that link the optimal MP values for each experimental catchment to different CPCs is undertaken for a set of nine "calibration" sub-catchments of the Alzette basin. They are representative of the different physiographic and geological types observed on the whole Alzette basin. The other 8 sub-catchments of the Alzette basin are used for the validation of these relationships.

Twenty-four daily raingauges and five hourly raingauges located inside or in the proximity of the Alzette basin were used to compute an average hourly rainfall series for each catchment. Series of daily potential evapotranspiration (*PET*) were calculated using the *Penman-Monteith* relation (Monteith *et al.*, 1990) from climatic data series available at the Luxembourg-City Airport station for different types of land use regrouped in permanent grassland, cropland, forest and urban areas. For each catchment, an average daily *PET* series was next determined according to the surface area proportion of each land use in that catchment.

Hydrological model description

For the present application we use a simplified version of the SOCONT hydrological model developed for small alpine catchments (Schaefli, 2005; Schaefli *et al*., 2005). This version is adapted for catchments with regimes not influenced by snow accumulation and melt processes. In this case, the model simulates a continuous hourly discharge series from only hourly rainfall and PET time series.

SOCONT is based on a deterministic, conceptual and "storage oriented" representation of the catchment hydrological behaviour. The model is expected to describe both the quick and slow components of the streamflow observed in the river. The total rainfall is thus divided after interception in infiltrated rainfall and net rainfall that supply the "soil reservoir" and the "quick flow reservoir", respectively. The model finally connects infiltrated and effective rainfall, as well as actual and potential evapotranspiration, through the filling rate of the soil reservoir, S/A, where A is the maximum storage capacity of the soil reservoir and S is the storage level, at time t. The baseflow discharge is linearly related to S. The net rainfall is routed through two non-linear reservoirs producing the fast component of flow.

The model has three parameters to be calibrated: A, the maximum storage capacity of the slow reservoir, and K and β the recession constants of the slow and rapid reservoirs, respectively.

Model calibration

The parameters optimization is a two-step and multi-signal manual procedure (Niggli *et al*., 2001). This method, which is only achievable because of the limited number of parameters, guarantees, in the opinion of the authors, a robust calibration, contrary to automatic calibration algorithms which are subject to many numerical uncertainties. The robustness of the calibration procedure used here is a necessary condition for regionalization works (Abdulla & Lettenmaier, 1997).

The parameters that condition the simulated baseflow component (provided by the model's soil reservoir) are calibrated so that the simulated baseflow reproduces at best a reference baseflow. The reference baseflow discharge series is obtained from the observed discharges series using a numerical hydrograph separation algorithm, the Baseflow Index method described by Kaden (1993).

The classical Nash criterion (Nash & Suttclife, 1970) was used to evaluate the model's ability to reproduce this reference baseflow. As already highlighted by Niggli *et al*., 2001, the only two parameters governing the baseflow, A and K, are correlated. A power function ($K = a.A^b$) provides a fairly good approximation of the relation between the different potentially optimal (A,K) sets (Fig. 2). Only a limited number of these couples provide an acceptable reconstitution of the simulated baseflow series. This acceptable range depends on the catchment. The exponent b of the A–K relationships is however more or less the same for all catchments (same slopes in the logarithmic plot in Fig. 2). Note that assuming a steady state of the slow reservoir behaviour (obtained for a constant rainfall intensity) and no losses via evapotranspiration, it is possible to analytically solve the ordinary differential equation governing the slow reservoir behaviour and to find the analytical expression of the baseflow discharge (equation (1)). This expression shows that the baseflow discharge only depends on a unique and global parameter $u = A.K$.

$$Q_{base}* = u\left[\sqrt{1+\left(\frac{u}{2.P_{eff}}\right)^2} - \left(\frac{u}{2.P_{eff}}\right)\right].S_{bv} \qquad (1)$$

where $Q_{base}*$ is the baseflow discharge obtained for a steady state behaviour of the slow reservoir when filled with a constant effective recharge rate P_{eff} and S_{bv} is the catchment surface area. As the real baseflow discharge $Q_{base}(t)$ is rather constant in

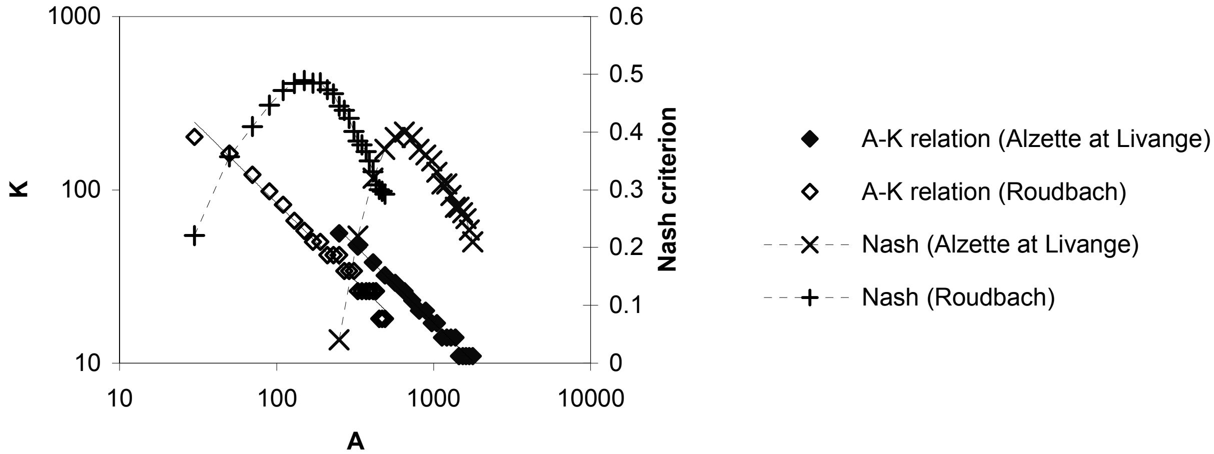

Fig. 2 log–log relation between *A* and K for two catchments and Nash criteria corresponding to each *A-K* couple.

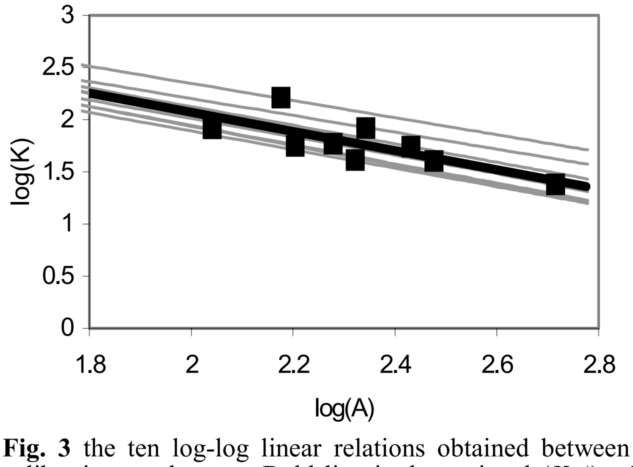

Fig. 3 the ten log-log linear relations obtained between *A* and *K* for the different calibration catchments. Bold line is the regional (*K,A*) relation, bold squares are the calibrated *A–K* couples.

time (when compared to the total discharge variations), the variable Q_{base}* corresponds in a first approximation to the mean baseflow value obtained with the mean effective rainfall intensity P_{eff} estimated for a N years observation period. Using the slow reservoir to reproduce the baseflow series or, more roughly, a given *BFI* value thus constrains the value of the u parameter and next the $A.K$ value.

The second step of the calibration procedure is to determine the best parameters A, K and β for the reconstitution of the total flow. The A and K values are here forced to follow the at-site $K(A)$ relationship previously calibrated. The optimal parameters set (A, $K(A)$, β) is identified for each studied catchment via the optimization of the objective function $C4$ estimated on the total discharges:

$$C4 = 1 - \frac{\sum_i \left(Qobs_i + \overline{Qobs}\right)\left(Qsim_i - Qobs_i\right)^2}{\sum_i \left(Qobs_i + \overline{Qobs}\right)\left(\overline{Qobs} - Qobs_i\right)^2} \qquad (2)$$

Criterion $C4$ was chosen because it gives more weight to high flows than the classical Nash-Sutcliffe criterion. Its optimal value is 1. For the nine calibration catchments, the $C4$ criterion value varies for the calibration period (1997–1998) from 0.71 to 0.86 and for the validation period (1999–2000) from 0.70 to 0.84.

Regionalization

The catchments are described by a number of physical descriptors relative to their morphology (such as the Gravelius coefficient, the elongation and relief factors, the maximal river network length and the maximal drainage density), to their geology (and especially the percentage of impervious substrate (marl, schist, clay or silt)) and to the land use (such as proportion of urban areas, cropland, forest, grassland and areas dedicated to mining extraction). No climatic characteristics were used because the hydro-climatologic environment is homogenous over the whole study area (Pfister, 2000). A preliminary analysis investigated the correlations between CPCs in order to identify possible interdependencies and to produce subsets of independent CPCs. For each of the three model parameters A, K and β, an automatic stepwise regression procedure (Draper & Smith, 1981) was next used to determine the most significant explanatory variables.

For parameter β (recession coefficient of the rapid reservoir), only variables relative to the catchment size (such as catchment area S, catchment perimeter P, river network length *LRES*) were significant at 5% level in the regression models. For the best regression, using the catchment surface area (S); the coefficient of determination value (R^2) calculated between calibrated and regionalized β values reaches 0.96 (equation (3)).

For the parameter A (maximum storage capacity of the slow reservoir), different regression models with similar performance were obtained. The two explanatory variables retained are the global slope index *IG* and the ratio of impervious substrates %*IMP*. The selected variables were significant at 5% level and the R^2 value calculated between calibrated and regionalized A values is 0.67 (equation (4)). Note that both variables can have a physical relationship with A. With a higher proportion of impervious substrates the catchment water storage capacity is lower, and the higher the slope the lower is the substrate depth and thus the storage capacity.

No explanatory variable was found to be sufficiently relevant for the K parameter (recession coefficient, slow reservoir). An estimate of K was obtained by the regionalization of the relations $K = a.A^b$ previously highlighted between A and K for each catchment. A least square adjustment was therefore made in a log-log diagram for A–K couples previously calibrated for each catchment (Fig. 2). The regional model for K estimation is then derived from this regional power function (equation (5)) and from the regional regression expression previously identified for A. The resulting regional model is rather efficient: the R^2 value reaches 0.60. In order to improve the K regional model, an attempt was made to regionalize the residuals of this relation. The improvement was not significant and the explanatory variables of the residuals were not relevant.

The three regional equations above were used to calculate the parameters for the nine calibration catchments and for the eight validation catchments. Figure 4 compares the regionalized (using the regional equations) and the calibrated parameters, for both calibration and validation catchments. The R^2 values for the validation catchments are 0.97, 0.58 and 0.35 for β, A and K, respectively. This confirms that the regionalized equation for β is the most successful whilst the equations determined for A and K are weaker, but nevertheless acceptable. These results correspond to those obtained from similar previous studies (Edijatno, 1991; Makhlouf, 1994): the most satisfactory regional equations also concerned the streamflow routing parameter, relating this parameter to the catchment area; it was however more difficult to develop significant equations for the water balance parameters.

Model Parameter	Regional equation	R^2	Equation
Recession coefficient, rapid reservoir	$\beta = 960.S^{0.73}$	$R^2 = 0.96$	(3)
Maximum storage capacity, slow reservoir	$A = 71600 \,.\, IG^{-0.38} \,.\, \%IMP^{-1.25}$	$R^2 = 0.67$	(4)
Recession coefficient, slow reservoir	$K = 8090 \,.\, A^{-0.92}$	$R^2 = 0.60$	(5)

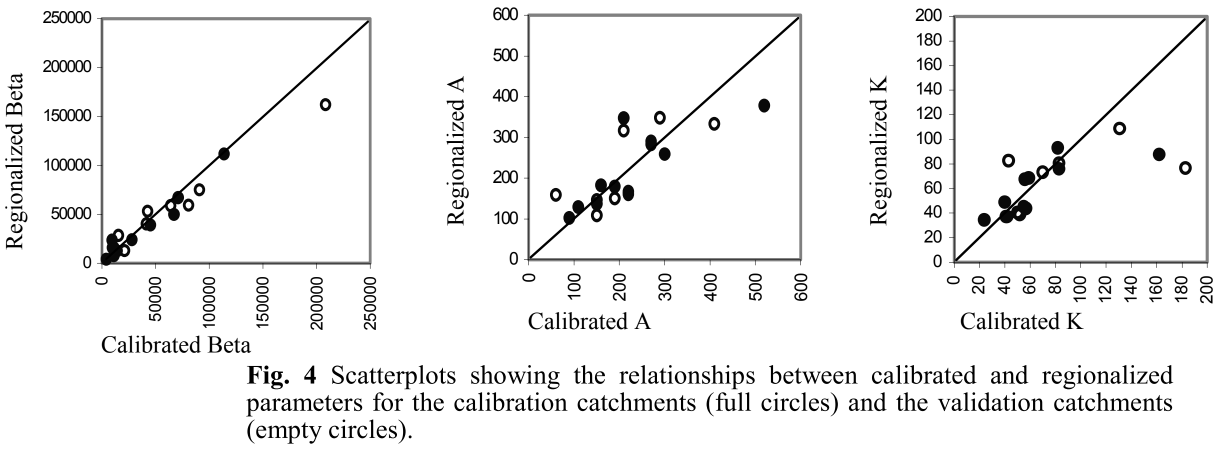

Fig. 4 Scatterplots showing the relationships between calibrated and regionalized parameters for the calibration catchments (full circles) and the validation catchments (empty circles).

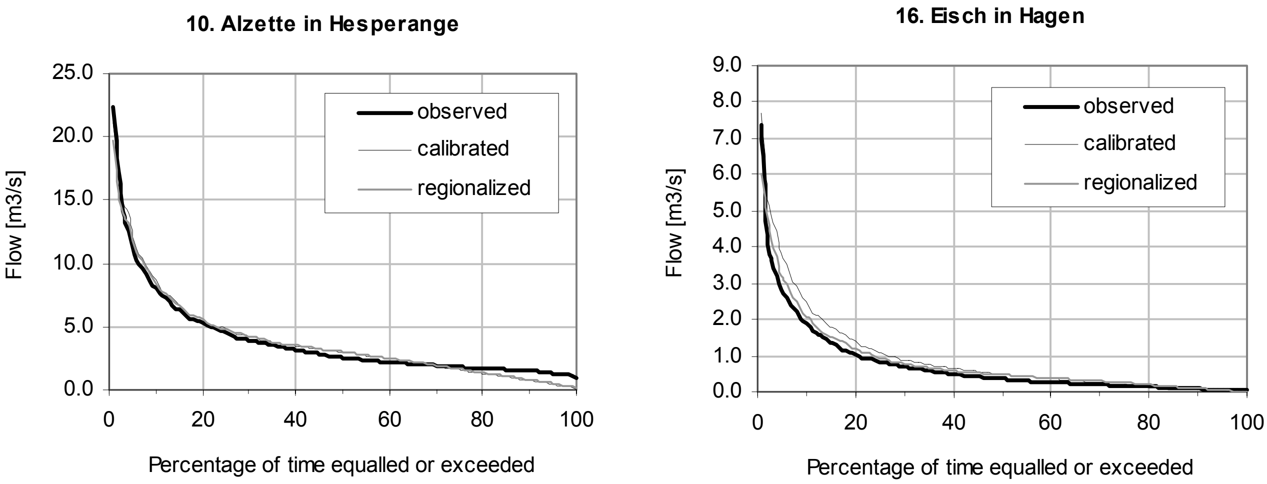

Fig. 5 Flow duration curves of observed, calibrated and regionalized flows for two of the validation catchments.

For four of the eight validation basins the *C*4 criterion values obtained for the total discharge with the regionalized model are equivalent to or higher than values obtained when the model is calibrated on the catchment. The *C*4 average value is 0.74 for the regionalized model and 0.81 when the model is calibrated, respectively. The flow duration curves of the observed, calibrated and regionalized flows (Fig. 5) for the validation catchments are very well reproduced for almost all catchments. The values of Nash efficiency coefficient calculated between simulated and observed daily flows from these curves are all above 0.95.

CONCLUSION

A parsimonious hydrological model was applied to simulate continuous hourly discharge series on several catchments of the Alzette Basin-Luxembourg characterized by various land use and lithological characteristics. The calibrated Model Parameters obtained for nine calibration sub-catchments were regionalized for the Alzette context and different regional equations were derived from a stepwise regression analysis linking these model parameters values to different Catchment Physical Characteristics.

The model, in its calibrated form as well as in its regionalized form, provides quite good results for the reproduction of the hourly discharges. The mean interannual discharges, the annual variability of hourly discharges (not presented) as well as the flow duration curves computed on daily discharges are very well reproduced.

The model requires only few data. It is thus possible to perform a very simple and robust manual calibration of its three parameters. Moreover, the regionalization work, if needed, may also produce, thanks to the relation highlighted between two of the three parameters, robust regional relationships between model parameters and catchment physical characteristics with both hydrological meaning and statistical significance. Such a simple rainfall–runoff model can thus provide an interesting simulation tool for practitioners that have to determine some important characteristics of flows for gauged and ungauged catchments.

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