# Calibration of a Parsimonious Rainfall-Runoff Model: a Sensitivity Analysis from Local to Regional Scale

G. Drogue

A. El Idrissi

L. Pfister

T. Leviandier

J. F Iffly

*See next page for additional authors*

## Presenter/Author Information

G. Drogue, A. El Idrissi, L. Pfister, T. Leviandier, J. F Iffly, and L. Hoffmann

# Calibration of a Parsimonious Rainfall-Runoff Model: a Sensitivity Analysis from Local to Regional Scale

**G. Drogue**[a,b], **A. El Idrissi**[a], **L. Pfister** [a], **T. Leviandier**[b], **J.-F. Iffly**[a], **and L. Hoffmann**[a]

[a] *CREBS-Cellule de Recherche en Environnement et Biotechnologies, Centre de Recherche Public – Gabriel Lippmann, L-1511 Luxembourg, Grand Duchy of Luxembourg (drogue@crpgl.lu)*

[b] *Centre d'Ecologie Végétale et d'Hydrologie, UMR-MA 102 ENGEES-ULP, F-67070 Strasbourg cedex, France.*

**Abstract:** Using a 4.25-year calibration period and 9 sub-basins (7 to 166 km$^2$) located in the Alzette river basin (Grand Duchy of Luxembourg), an analysis of relationships between optimal at-site parameters (OMP) of the conceptual HRM model and physical basin descriptors (PBD) was carried out in order to compare the model efficiency obtained for four regionalization procedures. The first procedure (P1) consisted in a spatial classification of basin response into 'physical' homogeneous clusters according to the OMP-PBD relationships. The second procedure (P2) is a regression-based approach which uses regional equations between OMP and PBD. The third procedure is a lumped regional procedure (P3) which estimates simultaneously a regional parameter set for all the basins. The last procedure is based on a spatial regional approach (P4) which used the semi-distributed version of the HRM model and fits simultaneously a regional parameter set for all the basins according to their geological heterogeneity. Significant correlation with some basin characteristics and noticeably, the permeability of geological formations and land uses (forest, grassland, cropland), could be found for two of the three free model parameters. The goodness-of-fit for the procedure P1 was slightly weaker than the calibration performs on each basin individually. Among the two procedures meaningful for transposition to ungauged basins, the spatial approach (P4) was close to the individual calibration procedure, and outperformed the regionalization of lumped parameters (P2), which was nearly as poor as the lumped regional model (P3). Although these results were obtained for calibration mode only, procedure P4, with few parameter values, should provide good predictions in validation mode.

***Keywords:*** Conceptual rainfall-runoff model; HRM model; Regionalization; Alzette basin; Luxembourg.

## 1. INTRODUCTION

Hydrological regionalization can be defined as a spatial classification and/or translation of hydrologically meaningful data [Hendricks, 1990]. The current research in regionalization aims at adding a spatial dimension to model parameters and thus transpose the results obtained on a local scale to a larger scale. As reported by Seibert [1999], a main difficulty in the application to basins of different sizes might be that parameter values in a lumped or a semi-distributed conceptual rainfall-runoff model are effective parameters at basin scale. Thus, it is interesting to know whether a regional parameter set which provides as accurate simulations as local ones (i.e. at basin scale) can be found. Furthermore, by looking for relationships between optimized parameter values and measurable physical descriptors, the model could be applied on non monitored basins within the region of interest for runoff prediction [Post and Jakeman, 1999]. Consequently, the existence of these relationships with objectively optimized parameters would support the physical basis of the model.

This study concentrates on 9 monitored sub-basins within the transnational Alzette basin (1176 km$^2$), a relatively small and fairly homogeneous region (Figure 1) from a climatic, hydrological and physiographical point of view [Pfister et al., 2000]. Using hourly rainfall-runoff series, the main goals were to apply the simple conceptual rainfall-runoff HRM model [Leviandier et al., 1994] in these basins for analysing the at-site variability of the optimal parameter values (OMP) with respect to basin attributes (PBD) and testing the sensitivity of the HRM model performance to the regionalization methods performed for its parameterisation.

The uncertainty in parameter determination influences the reliability of regional relationships between physical descriptors and optimal parameter values. A parsimonious and efficient model must therefore be used.

## 2. MATERIAL AND METHODS

### 2.1 The HRM model

The Hydrological Recursive Model is a rainfall-runoff model, which simulates hourly discharge using rainfall and potential evapotranspiration (PET) as input. It is composed of non linear loss and non linear upstream routing sub-models, a unit hydrograph, and a groundwater exchange sub-model. The coefficients of the unit hydrograph are interpreted as percentages of drained areas and the groundwater exchanges vary linearly from upstream to the outlet. In its lumped form, only four parameters are free and must be fitted. The upstream production and routing sub-model is based on the GR3/GR4 model [Edijatno et al., 1999]. In each reservoir the input of upstream outputs is delayed by an equal waiting time (isochronal zone) and each reservoir directly receives a part of excess rainfall. The model is called recursive because the structure at order n is obtained from the structure at order n-1 by a simple transformation (namely, routing + lateral input).

The four free parameters which must be fitted to run the HRM model are: i) parameter A (in mm) representing the maximum storage capacity of the soil reservoir filled up by a part of rainfall and emptied by evapotranspiration. When rainfall is higher than PET, the other part of rainfall (excess rainfall) is absorbed by the local routing reservoir, ii) the latter is emptied by a non-linear law, with a parameter, noted B (also in mm), which is the second free parameter of HRM, iii) the third parameter, noted $a_0$ ($km^2$) corresponds to the size of a sub-basin of order 1. This parameter represents a celerity in spite of its definition as an area. In the following application, due to some memory limitation encountered in the hourly version of the HRM model, it was applied with a value equal to 50 for all sub-basins and a number of reservoirs (16) of equal travel time. iv) Parameter d controls the groundwater exchanges : positive values give an infiltration upstream and an exfiltration downstream. Negative values are accepted, but their meaning is questionable. Due to the high parsimony of the model, the calibration does not encounter major difficulties and the multiple optima are rare [Edijatno et al., 1999]. The parameters are automatically optimised with the Rosenbrock procedure.

### 2.2 Study area and data processing

The HRM model was first calibrated individually for each of the 9 monitored sub-basins within the transnational Alzette basin presented in Table 1. The area of the sub-basins ranges from 7 to 166 $km^2$. The elevation is quite homogeneous as the average basin altitudes ranges from 295 to 390 m.a.s.l. Among the selected sub-basins, four are homogeneous from a lithological point of view, with essentially marls (Mamer upstream, Mess, Eisch upstream, Attert at Reichlange), while the other basins are composites with marls, limestone, sandstone and schists. The geological formations partially condition the land use patterns. Thus, in general, agricultural areas coincide with marls and forested areas with sandstones. Most of the basins can be considered as rural and forested basins.

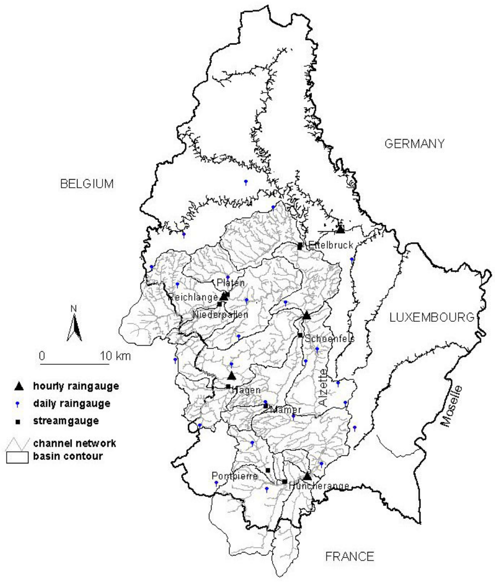


**Figure 1.** Study area and monitoring networks

The 'at-site' model calibration was carried out for the HRM parameters using measured hourly discharges from January 1997 to March 2001. Based on daily rainfall information collected by twenty-four rain-gauges, the hourly areal rainfall was calculated for each basin using the following procedure: for a given basin, the daily areal rainfall estimated with Thiessen polygons was disaggregated according to the time structure of rainfall measured at a hourly reference raingauge (Figure 1). Potential evapotranspiration was estimated using the Penman-Monteith formula [Monteith and Unsworth, 1990] with daily meteorological data measured at Luxembourg airport. The same climatological data series were therefore uniformly applied on the whole study area. Some parameter values involved in the PET formula, like canopy resistance, albedo and vegetation height were taken from literature according to the land use types of the basins.

An average daily PET was determined for each basin as the sum of four PET per land use types

**Table 1.** Characteristics of the selected sub-basins within the Alzette basin

| River | Outlet | Abrev. | Area ($km^2$) | Urban area (%) | Agricultural area (%) | Forested area (%) | IMP (%) | PER (%) |
|---|---|---|---|---|---|---|---|---|
| Attert | Reichlange | AR | 166.0 | 4.0 | 60.9 | 34.9 | 83.4 | 16.6 |
| Eisch | Hagen | EH | 47.2 | 6.4 | 76.3 | 17.3 | 86.4 | 13.6 |
| Mess | Pontpierre | MP | 36.1 | 11.1 | 80.2 | 8.7 | 91.6 | 8.4 |
| Mamer | Mamer | MM | 18.3 | 8.9 | 80.6 | 10.5 | 88.0 | 12 |
| Mamer | Schoenfels | MS | 84.7 | 11.6 | 56.6 | 31.6 | 51.9 | 48.1 |
| Mierbech | Huncherange | MH | 7.2 | 6.2 | 61.7 | 32.0 | 95.2 | 4.8 |
| Pall | Niederpallen | PN | 34.6 | 3.9 | 70.7 | 25 | 66.8 | 33.2 |
| Roudbach | Platen | RP | 47.1 | 4.8 | 58.2 | 36.7 | 59.1 | 40.9 |
| Wark | Ettelbruck | WE | 82.2 | 4.3 | 52.7 | 42.9 | 56.4 | 43.6 |

IMP: Impermeable geology is substratum with dominance of marls, schists, clay or silt
PER: Permeable geology is substratum with dominance of sandstone

(proportion of urban areas, proportion of croplands, proportion of grassland, proportion of forest). Each daily PET series was disaggregated at an hourly time step according to the sunshine duration measured at Luxembourg airport.

## 2.3 Model evaluation

Goodness of fit after calibration was estimated through the ability of the HRM model to reproduce the hydrographs through the Nash and Sutcliffe coefficient [Nash and Sutcliffe, 1970]:

$$E = 1 - \frac{\sum_i \left(Q_{sim_i} - Q_{obs_i}\right)^2}{\sum_i \left(Q_{obs_i} - \overline{Q_{obs}}\right)^2} \qquad (1)$$

where $Q_{sim}$ is the simulated streamflow, $Q_{obs}$ the measured streamflow and $\overline{Q_{obs}}$ the average streamflow value on the measurement period.

# 3. RESULTS OF THE INDIVIDUAL CALIBRATION

## 3.1 Performance of the optimal parameter values

The numeric values of the Nash and Sutcliffe coefficient show that the HRM model is able to provide good fits to the hydrographs with values of E varying between 0.73 and 0.86 for the whole set of basins (Figure 5). The mean value of E is around 0.79. The small marly basins are much more difficult to reproduce with the HRM model.

## 3.2 Correlation between parameters and PBD

Hydromorphometric, land cover and geological data were determined for each basin via the Spatial Analyst module of ArcView. All of the three parameters were significantly correlated to at least one PBD (Figure 2). A rather good and expected correlation exists between parameter A and the percentage of permeable geological substratum formations, as well as the percentage of croplands. A significant correlation with geology also emerges for parameter B, as well as with the slope index (IG), the relief factor (FR) and the percentage of forested areas (FOR).

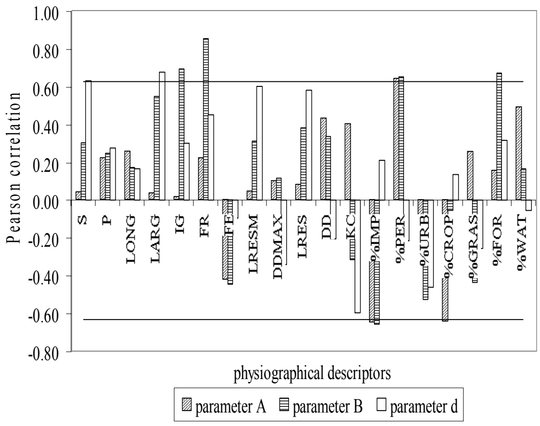


**Figure 2.** Correlation between PBD and model parameters (straight line: $r_\alpha \approx 0.63$ at 5 % level)

S: Surface ($km^2$), P: Perimeter (km), KC: Gravelius Shape Coefficient, LONG: Equivalent length (km), LARG: Equivalent width (km), IG: Global slope index (m/km), FR: Relief factor (m), FE: Elongation Factor, LRESM: Maximum network length (km), DDMAX: Maximum drainage density ($km.km^{-2}$), LRES: Normal network length (km), DD: Normal drainage density ($km.km^{-2}$), %IMP: Proportion of impervious substrate, %PER: Proportion of pervious substrate, %URB: Proportion of urban areas, %CROP: Proportion of croplands, %FOR: Proportion of forest, %GRAS: Proportion of grassland, %WAT: Proportion of lakes and ponds.

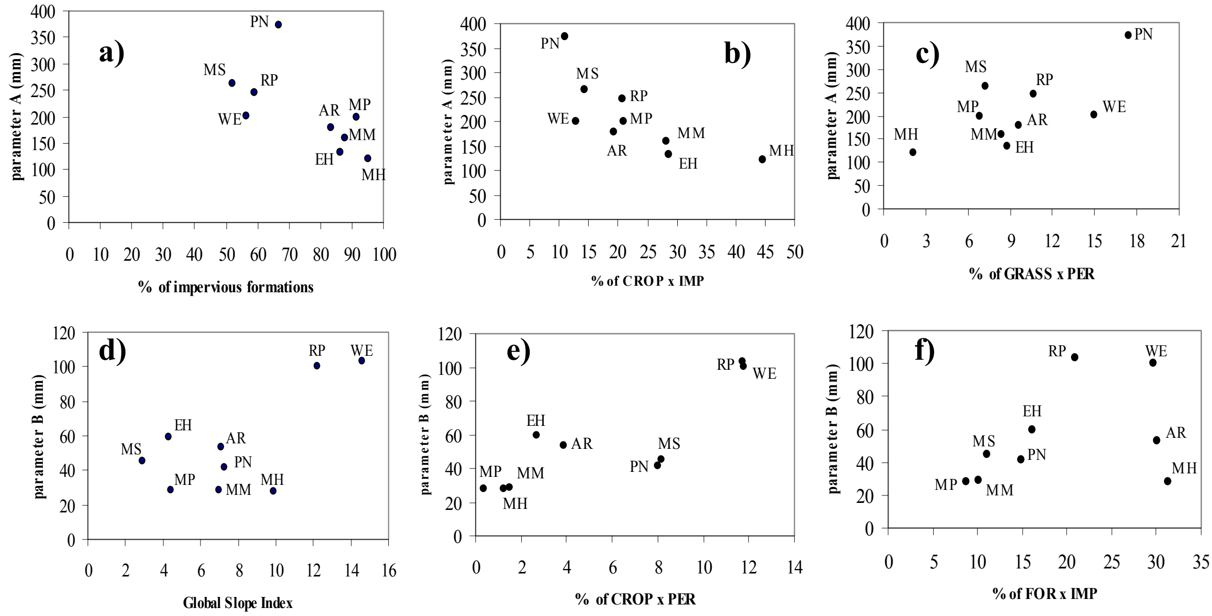


**Figure 3.** Best model parameter values of A and B according to the E coefficient against significant PBD

The variability of the groundwater exchange intensity parameter (d) seems to be less explainable by the selected PBD.

As the land use patterns and permeability of geological formations seem to be the better descriptive factors of the parameter's variability and as they are sometimes inter-correlated, the optimal values of the two reservoir parameters were plotted against new PBD obtained by a product of those two physiographical parameters (Figures 3 b, c, e, f).

Parameter A, which represents the retention capacity of the soil reservoir, rather than a (decreasing) index of permeability, is lower on impervious formations than on pervious ones (Figure 3a). This means either that these properties are difficult to separate at the scale of the model, or that they are statistically linked. The scatter plot could be divided into two groups of basins opposing the marls and the sandstone basins. The higher A value of PN seems to be conditioned by the fact that the percentage of croplands on its impervious formations is the lowest in comparison to other basins (Figure 3b) in favour of grassland on its pervious formations (Figure 3c). A stronger correlation ($r \approx .76$) was found to exist between A and CROPxIMP (Figure 3b) and between B and CROPxPER ($r \approx .82$) as depicted by Figure 3e.

Decreasing values of B (quicker runoff) can be expected for increasing slope indexes, if slope is not taken into account by the parameter $a_0$ (kept constant in our simulations). This is coherent with results found previously, though opposite results may also be encountered [Leviandier et al., 2002].

In the Alzette sub-basins, the general trend is observed, excepted for two outliers (RP and WE basins) with high slope index and high values of B. This leads to a paradoxical positive correlation if they are kept in the same sample (Figure 3d).

The unexpected RP and WE values for B according to the slope are also extreme with respect to the proportion of pervious formations (Figure 3e). The role of subsurface runoff generation due to steep slopes on impervious formations (schists) in the upper part of those two basins is probably mitigated by the permeability of sandstone formations partly recover with croplands lying in their central part (Figure 3e).

If the trend in the Figure 3e is considered, one can see that the PN and MS basins have a low B value. The influence of sandstones formations in runoff production is probably less obvious than in the two other composite basins (RP, WE) due to their spatial distribution in the basins (Figure 4). Figure 3f shows that for the marly basins, the optimal values for B are slightly modified by the percentage covered by forested areas.

## 4. ESTIMATION OF THE REGIONAL PARAMETER SETS

### 4.1 Presentation of the four procedures

<u>Procedure 1</u> (P1): The lumped version of the HRM model was first applied separately to 5 clusters. Considering the at-site optimal A and B values and their relationships with PBD (see above), it gives 5 homogeneous parameterisations with physical coherence:

Cluster 1: MH, MP, MM (small marly basins)
Cluster 2: EH, AR (marly basins with more permeable formations: alluvium and sandstones)
Cluster 3: RP, WE (composite basins with runoff production dominated by permeable formations)
Cluster 4: PN (composite basins with low percentage of croplands and higher percentage of grasslands on permeable formations instead of forests)
Cluster 5: MS (composite basins with runoff production dominated by impervious formations)
A unique parameter set (A, B $a_0$, d) was fitted on each of these groups (i.e. multi-site calibration).

Procedure 2 (P2): For A, a power model was fitted while for B, a linear model was identified by a multiple step by step regression analysis using the best relationships of Figure 3 and independent PBD. The regional equations fitted on the 9 basins are the following:

$$A = 1594.4\ \%CROPxIMP^{-0.6934} \quad R^2 = 0.7625 \quad (2)$$

$$B = 12.853 + 0.717\ \%FORxIMP + 5.057\ \%CROPxIMP \quad R^2 = 0.739 \quad (3)$$

The two regional values obtained through P3 for $a_0$ and d were used to complete the parameter sets for each basin.

Procedure 3 (P3): A lumped regional parameter set (A, B $a_0$, d) was fitted to the 9 runoff series (i.e. multi-site calibration).

Procedure 4 (P4): The assumption that contrasted hydrological behaviours are to be found among contrasted physical zones was tested. For this purpose, lithologically dependent parameters were identified, using the intersection of real homogeneous areas with hypothetical isochronal zones of the HRM model [Leviandier et al., 2002]. The latter method defines a primary level of spatial discretization (the variability within them is ignored) able to reveal a coarse scale heterogeneity of basins (yet finer than any typology of basins described by percentage of their whole area). In this approach, the simulated hydrograph at the basin outlet being the sum of the contribution of each physical class defined by the user and there is no averaging of parameters. The relationships between the at-site version of the HRM parameters and PBD described above indicate a significant spatial variation of the local production and routing parameters A and B according to the geological permeability. The latter was chosen as a non varying geographical factor in space and time. Four physical classes were therefore defined including two values of A and two values of B, the first representing the impervious formations and the second the pervious formations.

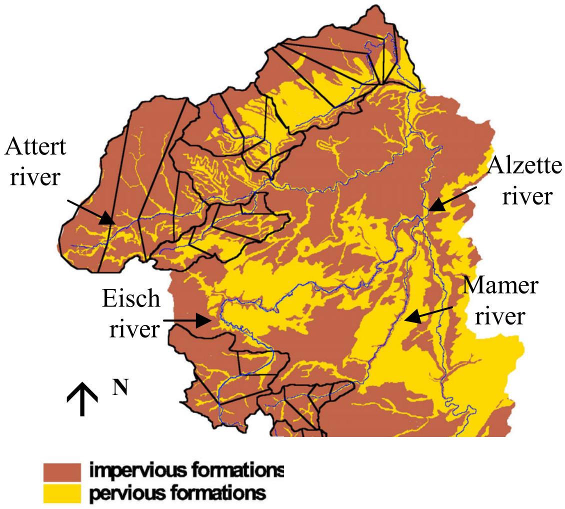


**Figure 4.** Examples of basins partitioned into isochronal zones and spatial distribution of the two types of lithology in the Alzette river basin

The 9 basins were partitioned into isochronal zones which were intersected with the permeability of geological formations (Figure 4) in order to get a percentage of this information versus the number of linear operators representing routing for all of the 9 basins. The number of reaches is determined by the user according to the physical heterogeneity of the studied basin and the total number of reservoirs used by the model (16 in our case). The areas of lateral input flows for each order of the model are calculated according to an area/length relationship and drawn with straight and continuous lines crossing the main stream at the limits of reaches (Figure 4). Parameters $a_0$ and d were not regionalized and a unique value per parameter was fitted simultaneously with the 4 values of A and B (A1, A2, B1, B2, $a_0$, d) on the 9 runoff series.

## 4.2 Efficiency of the local and regional parameter sets

The statistics of the efficiency values obtained for each of the calibrations and each basins are summarized in Figure 5. The lumped calibration for the 5 basin clusters is slightly weaker and performed equally well than the individual calibrations even though its range is slightly more important. The mean efficiency of the physically-based regionalized model (spatial estimation) is also satisfactory, while the lumped regional calibration and the regression-based approach are characterized by a mean efficiency below an acceptable threshold (≈ .70) and a great magnitude of error.

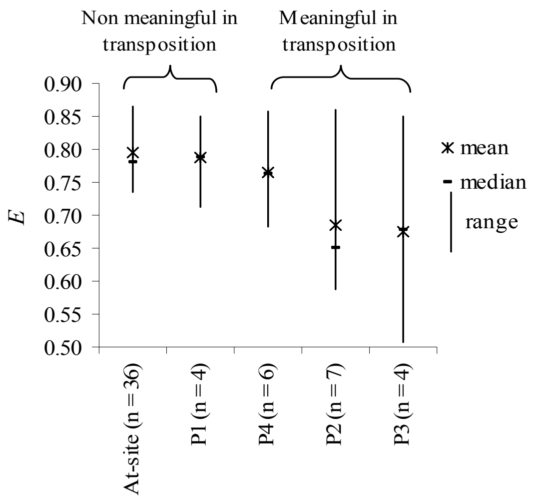


**Figure 5.** Goodness of runoff series obtained for local and regional parameter sets (all the basins; n: number of parameter values)

The lumped regional calibration applied on homogeneous basin clusters is able to provide good results but suffer from a lack of transposition, since the criteria of classification and the boundaries between clusters are still approximate. It would be more advisable to use the spatial regional parameter set for making streamflow estimations on ungauged basins.

## 5. CONCLUSIONS AND PERSPECTIVES

The parsimonious HRM model was run on different scales (from local to regional) and with a variable degree of spatial discretization for regionalization purposes (from lumped to spatial estimation). The geological heterogeneity of the Alzette basin is such that a unique lumped regional estimation of model parameters is unacceptable, but simple enough to detect land use patterns as significant. Strong correlations between at-site model parameters and basin characteristics were found, as a consequence of a fairly good efficiency of the model and pertinence of selected PBDs.

They were used to calculate regional equations and design a typology of basins consisting of five clusters, as well as a typology of two contrasted lithological classes. Among the four tested regionalization procedures, only the lumped estimation of parameters applied to basin clusters and the spatial regional estimation of parameters based on the concept of lithological contrasted zones provides good runoff estimation. This finding is encouraging in view of transposition to ungauged basins, especially for the spatial method.

In future work, the regionalization method should be improved by taking into account the joint contribution of geology and land use patterns.

## 6. ACKNOWLEDGMENTS

This study was partially funded by the Luxembourg Ministry of Education. Support was also provided by the FRHYMAP project within the IRMA-SPONGE research programme.

## 7. REFERENCES

Edijatno, N., N.O. Nascimento, X. Yang, Z. Maklhouf and C. Michel, GR3J: a daily watershed model with three free parameters, *Hydrological Sciences Journal*, 44, 263-277, 1999.

Hendricks, M.R., Regionalisation of hydrological data. Effects of lithology and land use on storm runoff in east Luxembourg, PhD thesis, Amsterdam, 168 p., 1990.

Leviandier, T., G. Mantilla-Moralles, and 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 p., 1994.

Leviandier, T., N. Siefert, Z. Ahmed, and J. Humbert, Are landscape contrasts perceptible from downstream ? *Journal of Hydrology,* submitted, 2002.

Monteith, J. L., and M. Unsworth, Principles of Environmental Physics, 2nd ed., Edward Arnold, 291 pp., London, 1990.

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.

Pfister, L., J.F. Iffly, A. El Idrissi, and L. Hoffmann, Vérification de l'homogénéité physio-géographique, hydrologique et climatique du bassin de l'Alzette (Grand-Duché de Luxembourg) en vue d'opérations de régionalisation, *Archives de l'Institut Grand-ducal de Luxembourg. Section des Sciences Naturelles, Physique et Mathématiques*, 43, 239-253, 2000.

Post, D.A., and A.J. Jakeman, Predicting the daily streamflow of ungauged catchments in S.E. Australia by regionalising the parameters of a lumped conceptual model, *Ecological Modelling*, 123, 91-104, 1999.

Seibert, J., Regionalization of parameters for a conceptual rainfall-runoff model, *Agricultural and Forest Meteorology*, 98-99, 279-293, 1999.