REGIONAL REGRESSION FORMULAE FOR ESTIMATION OF RAINFALL - RUNOF MODEL PARAMETERS IN UNGAUGED CATCHMENTS.

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Abstract:

In the paper a modification of a common procedure used in model parameter estimation in ungauged basins was presented. The Hron River basin located in Central Slovakia was selected as a pilot region. The applicability of the concept was tested in selected the 23 subcatchments of the basin. In the first step, the concept was based on the subdivision of the region of interest to pooling groups with similar physiographic characteristic using clustering method. Subsequently parameters of a lumped rainfall – runoff model were estimated by calibration using a daily time step in subcatchments. Regional regression formulae for the estimation of rainfall-runoff parameters from catchment characteristics were derived separately for each pooling group. Finally the assumption was tested that in catchments selected according to a similarity measure, such relationships may perform better than in arbitrarily chosen catchments.

Key words: model parameters, pooling scheme, multiple regression

Introduction

Methods for transferring model parameters from gauged to ungauged catchments are needed in water resources modeling studies in poorly gauged regions. Although a great deal of experience has been gained with parameter estimation methods for ungauged catchments, there is a continuing need to upgrade these methods and to test them against practical requirements, since the problem of regional parameter estimation still constitutes the largest obstacle to the successful application of models in ungauged catchments.

The widespread technique to predict daily runoff in ungauged sites nowadays is to use some of various rainfall-runoff models. The procedure of application rainfall-runoff models usually consists of model calibration (finding optimal model parameter values that cannot be measured in the field) on gauged catchments (Klemeš, 1986) and transferring the parameter values to ungauged catchments. Authors start to deal with assessing the hydrological response in ungauged catchments by the models since 1970's. Ross (1970) related parameter values of conceptual model to two catchment characteristics (plant available water capacity and soil permeability) in 16 catchments and found high correlations, while Magette et al. (1976) derived multiple linear regression equations (multiple regression coefficients over 0.8) using up to 6 of the 15 catchment characteristics to fit the 6 model parameters.

Weeks and Ashkanasy (1983) related 9 of the 16 parameters of Sacramento model to 6 catchment characteristics and get satisfactory results with regional parameters. Hughes (1989) formulated relationships between 8 of the 12 event based conceptual model parameters and combinations of 2 to 5 of the 13 physical catchment characteristics using 33 catchments in South Africa and USA. Two lumped, conceptual models (with 7 and 3 parameters) were applied to 20 catchments in Ivory Coast by Servat and Dezetter (1993). Vandewiele et al. (1991) indicated correlations between the 3 model parameters of physically-based model and the percentage of porous subsurface of the 24 Belgian catchments.

Kokkonen et al. (2003) concluded that high significance of regression between model parameter values and catchment characteristics does not guarantee a set of parameters with a good predictive power when applied to ungauged catchment, consideration of interrelations between model parameters can improve performance of regression as a regionalisation method and that care must be taken when interpreting physical meaning behind distinguished model parameter - catchment attributes relationship. Spate et al. (2004) or Croke and Norton (2004) proposed alternative regionalisation approach for prediction of flow characteristics in ungauged catchments. Key catchment response characteristics (mean annual runoff coefficient, slope of the flow duration curve, fraction of time without flow, form of the unit hydrograph) are regionalised directly and used to constrain the model parameters, rather than regionalising model parameters.

Merz and Blöschl (2004) used physiographic catchment characteristics to estimate the HBV model parameters in selected catchments of Austria. They realised that in general the correlations between model parameters and catchment attributes were not high. Two explanations were given by authors: first, that catchment attributes may not significantly affect hydrological response and the second is that there may be a significant uncertainty in calibrated parameter values, which can cloud the model parameter-catchment attributes relationship.

In Slovakia, the attempt to estimate model parameters using multiplicative regression formulae was tested in the upper Hron region in Kohnová et al. (2004), where regression formulae for model parameters were derived for all catchments in the region.

Study area

The pilot basin selected for this study is located above the gauging station Brehy of the Hron River basin with an area of 3821 km^2 in the middle part of Slovakia. The flood formation problem in the Hron basin is complex and is characteristic for the mountainous regions of the country. In the alpine high mountain regions flash floods represent a threat to local villages build in narrow valleys. Due to the character of runoff concentration floods from rainfall of cyclonic origin represent main danger to major cities and industrial areas with heavy and chemical industry, electric and atomic power plants in the middle part and the lowest part of the catchment.

Digital elevation model, river network and gauge stations in analysed sub-catchments of the Hron River basin in Slovakia is shown in Fig. 1. The minimum elevation of the basin is 195 m a. s. l., the maximum elevation is 2043 m a. s. l. and the mean elevation is 690 m a. s. l. Region of the Hron River basin was divided to 23 sub-catchments with available daily flow, precipitation and air temperature time series needed for calibration to obtain model parameter values.

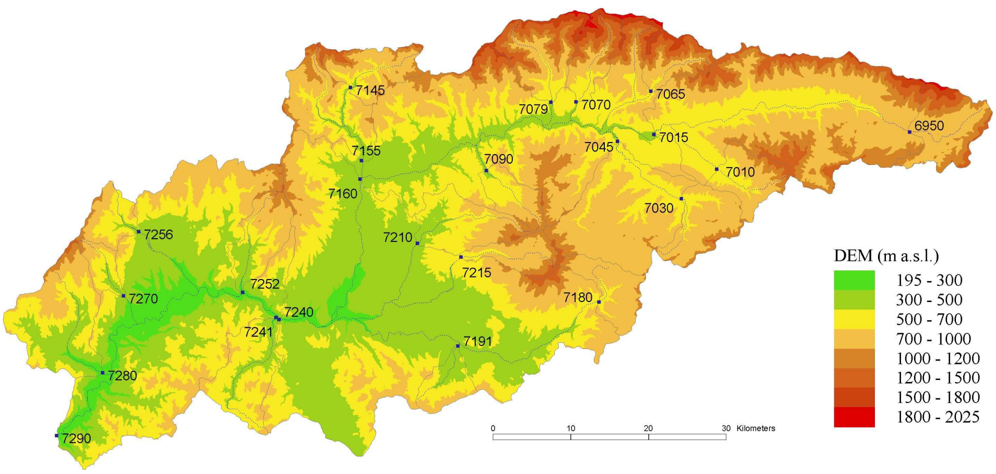

Fig.1 Digital elevation model, river network and gauge stations in analysed sub-catchments

Table 1. List of selected gauging stations

Id code	Gauging station	River	Id code	Gauging station	River
6950	Zlatno	Hron	7180	Hriňová n/vn	Slatina
7010	Michalová	Rohozná	7210	Zolná	Zolná
7015	Brezno	Hron	7215	Hrochoť	Hučava
7030	Čierny Balog	Čierny Hron	7240	Hron. Breznica	Hron
7045	Hronec	Čierny Hron	7252	Trnavá Hora	Ihráčsky p.
7065	Mýto pod Ďumb.	Štiavnička	7280	Žarnovica	Kľak
7070	Dolná Lehota	Vajskovský p.	7290	Brehy	Hron
7079	Jasenie	Jaseniansky p.	7191	Pstruša	Kocanský p.
7145	Staré Hory	Starohorský p.	7241	Hron. Breznica	Jasenica
7155	Banská Bystrica	Bystrica	7090	Ľubietová	Hutná
7160	Banská Bystrica	Hron	7256	Janova Lehota	Lutilský p.
			7270	Horná Ždaňa	Prochotský p.

Following average values of physiographic characteristics were derived for each sub-catchment using GIS: catchment area [km^2] (F), mean elevation of the catchment [m a. s. l.] (PR VÝŠKA), mean catchment slope [%] (PR SKLON), aspect of the catchment [º] (OR), shape of the catchment [-] (TVAR POV), river density [$km.km^{-2}$] (HUS SIETE), mean slope of the river [%] (SKLON HL), time of concentration according to the Kirpich formula [h] (Tc-KIR), hydrogeological basin index [-] (HG CHAR), infiltration index [-] (Kr), forested area [%] (LES), long-term mean annual temperature - 1931-1980 [ºC] (TEP REG), maximum daily precipitation totals - 1931-1980 [$mm.day^{-1}$] (ZR MAX), long-term mean annual precipitation totals- 1931-1980 [mm] (P), long-term maximum snow cover depth with return period of 100 years- 1931-1980 [cm] (SNEH 100), long-term mean annual runoff – 1931-1980 [$l.s^{-1}.km^{-2}$] (ODTOK).

Model calibration

The Hron rainfall-runoff model, which was developed at the Slovak University of Technology in Bratislava (Kubeš, 2002), was used in this study. This conceptual semi-distributed model is based on the principles of the HBV model (Bergström and Forsman, 1973) and contains three basic storage components with 15 calibrated parameters. Surface and subsurface processes can be modeled separately for elevation zones, and the model parameters can also be set up separately for the sub-basins.

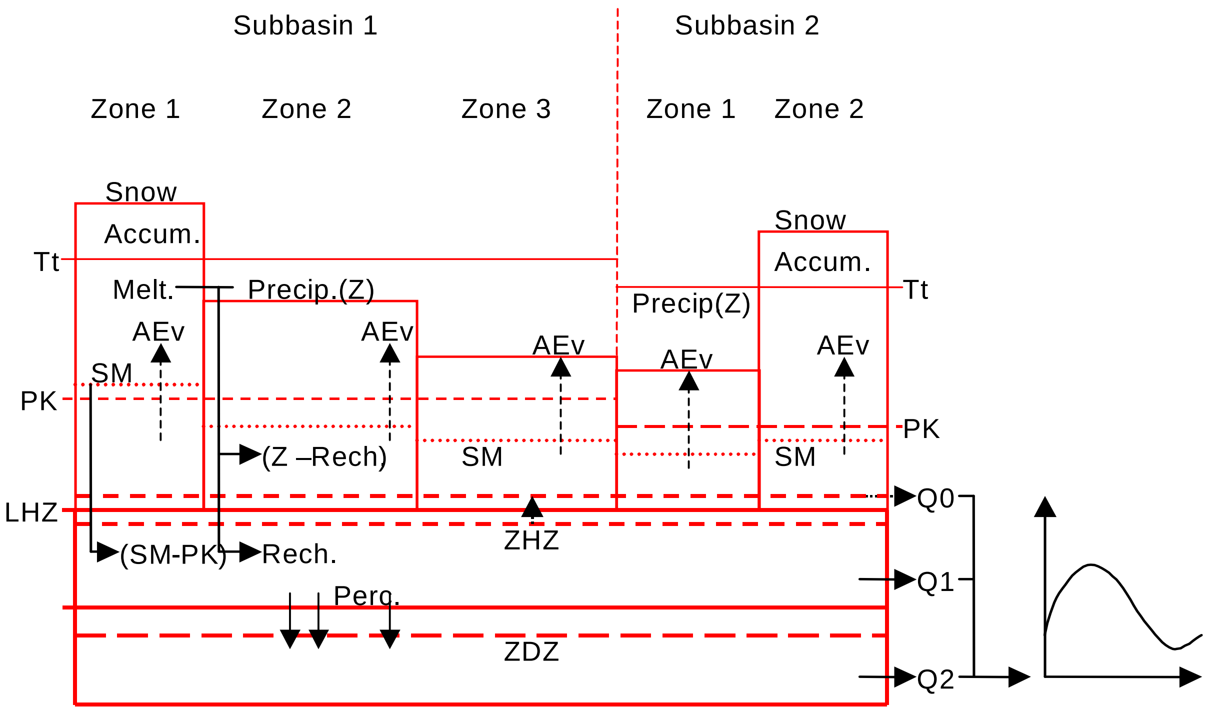

Fig. 6. *General scheme of the Hron rainfall-runoff model: Z – precipitation and/or snowmelt water (mm), Tt – the snowmelt threshold temperature (°C), AEv - actual evapotranspiration (mm), PK – field capacity (mm), SM – soil moisture (mm), LHZ – upper reservoir limit (mm), ZHZ – storage in upper reservoir (mm), ZDZ – storage in lower reservoir (mm), Rech. – groundwater recharge (mm), Perc. – percolation rate (mm/day), Q0 – surface runoff (if ZHZ exceeds LHZ) (mm), Q1 – subsurface runoff (mm), Q2 – base runoff (mm).*

The snow sub-model uses the degree-day method for snow accumulation and snowmelt calculations. The sub-model for soil moisture simulation contains 4 parameters and calculates the soil water storage, groundwater storage and actual evapotranspiration from the soil profile depending on the relation between the water content in the soil profile and the field capacity value. The runoff sub-model with six parameters consists of one nonlinear and one linear reservoir and simulates both quick and slow runoff components (surface and subsurface runoff and base flow). The recharge is added to the upper reservoir with the actual capacity *ZHZ* (mm). If the *ZHZ* is above the maximum threshold capacity for subsurface runoff generation *LHZ* (mm), the surface runoff starts. The parameter *PER* (mm/day) defines the maximum percolation rate from the upper zone to the lower reservoir with the capacity *ZDZ* (mm). The basin runoff is calculated as the sum of all the partial runoffs, and it is routed by a discrete cascade of linear reservoirs with a discharge-dependent time parameter (multilinear cascade model).

Input data needed for runoff simulation with a daily time step are:

- catchment's average mean daily precipitation values,
- catchment's average mean daily air temperature values,
- long-term mean monthly potential evapotranspiration and
- long-term mean monthly air temperature values.

It is also possible to use daily potential evaporation values if they are available. In order to calibrate the model parameters, the mean daily discharge values in the closing profile of the selected basin are needed. A more detailed description of the model is given in Kubeš (2002).

For calibration of the model parameters in our study the time period (1991 - 2000) was used. The time period (1981 – 1990) was left for validation of the model.

Identification of pooling groups within Hron region

Numerous techniques have been used to identify pooling groups for regional analysis. The widespread method used for delineating hydrologically homogenous regional types – pooling groups, is grouping according to geographical similarity, or application of multivariate techniques as cluster analysis (Nathan and McMahon, 1990; Burn, 1990). Here, physiographic properties of basins and climatic characteristics were used as variables in the cluster analysis to pool catchments into groups. Several methods of hierarchical clustering were tested. K-means clustering with Euclidean metrics after Hartigan (1975) with the same weight assigned to each characteristic in the clustering process was selected as the most suitable pooling method.

Applying cluster analysis all sub-catchments were divided to 3 pooling groups. Several combinations of pooling characteristic were tested. Here the results of pooling according to the aspect of the catchment [°] (OR), hydrogeological basin index [-] (HG CHAR), forested area [%] (LES) and maximum daily precipitation total - 1931-1980 [mm.den^{-1}] (ZR MAX) are presented in Fig.2.

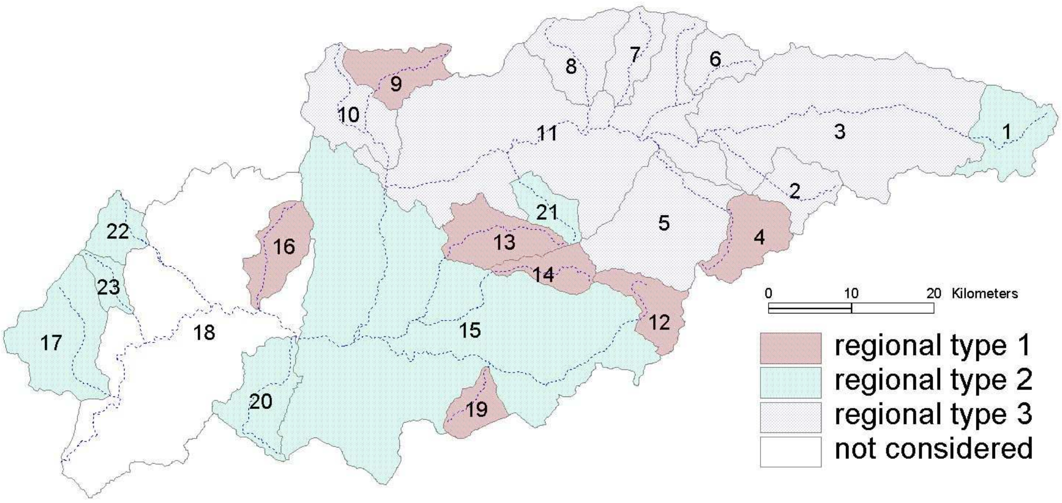

Fig. 2 Pooling scheme of analysed sub-catchments

Regional Regression Formulae

In the fist step the regional regression formulae were derived for the whole Hron region as one pooling group, in the second step for the three selected pooling groups. A stepwise multiple regression was used to determine the relationship between the climatic and physiographic basin characteristics and the model parameter values in the region. Attention was paid to the minimisation of the effect of multicollinearity by choosing predictors with low interdependence. Following multiplicative linear regression model was selected to derive at regional model parameter values:

$$MP = a * Ch1^{\,b} * Ch2^{c} * \ldots * \; Chn^{m} \qquad (1)$$

where: MP - model parameter value, Ch1-n - selected physiographic characteristics and a, b...m - regression coefficients.

Different starting variables and variable sets were selected in a trial and error manner. Several sets were considered, each run starting with a simple regression with that independent variable with the strongest influence on the dependent variables. Pearson correlation coefficients were chosen as a measure of dependence between the predictors. Several subjectively chosen and hydrologically reasonable starting combinations of the independent variables were used as seeds in the discrimination process. The values of the multiple correlation coefficients were in average about 0.8 for the resulting combinations of predictors. Different combinations of independent variables gave statistically comparable results. Following regression formulae for estimation of model parameters were derived for each of selected pooling group (Tab. 2).

Table 2. Model parameters, multicorrelation coefficients (R) and regional regression formulae derived separately for each pooling group 1-3.

Pooling group 1

Model parameter	**Multiple R**	**Regional Regression Formulae**
DDF	0.821	$\text{DDF}=e^{8,373}.\text{SNEH100}^{-0,664}.\text{PR\_VÝŠKA}^{-0,732}$
Tt	0.883	$\text{Tt}=e^{-10,68}.\text{LES}^{0,751}.\text{ODTOK\_31-80}^{3,928}$
WHC	0.794	$\text{WHC}=e^{34,381}.\text{Faško}^{-6,031}.\text{HUS\_SIETE}^{8,392}$
RFC	0.852	$\text{RFC}=e^{-4,317}.\text{ODTOK\_31-80}^{0,686}.\text{SNEH100}^{0,431}$
SFC	0.8	$\text{SFC}=e^{-2,862}.\text{ODTOK\_31-80}^{0,554}.\text{Kr}^{-1,119}$
PK	0.882	$\text{PK}=e^{6,798}.\text{ODTOK\_31-80}^{-0,383}.\text{LES}^{0,703}$
LPE	0.806	$\text{LPE}=e^{-17,695}.\text{Kr}^{-1,526}.\text{Faško}^{2,254}$
Rech	0.781	$\text{Rech}=e^{2,102}.\text{SNEH100}^{-0,187}.\text{tc-KIR}^{-0,084}$
EMP	0.548	$\text{EMP}=e^{-14,799}.\text{Kr}^{-10,431}$
K0	0.87	$\text{K0}=e^{-2,248}.\text{LES}^{12,809}.\text{DL\_TOKU}^{0,310}$
K1	0.742	$\text{K1}=e^{9,113}.\text{tc-KIR}^{-0,216}.\text{ZR\_MAX}^{-2,230}$
K2	0.958	$\text{K2}=e^{4,32}.\text{LES}^{3,797.}\text{OR}^{-0,952}$
LHZ	0.906	$\text{LHZ} =e^{4,464}.\text{HUS\_SIETE}^{-5,73.}\text{TVAR\_POV}^{-1,032}$
PER	0.918	$\text{PER}=e^{-7,115}.\text{HG\_CHAR}^{1,605}.\text{SKLON\_HL}^{0,116}$

Pooling group 2

Model parameter	**Multiple R**	**Regional Regression Formulae**
DDF	0.789	$\text{DDF}=e^{1,927}.\text{SNEH100}^{-0,237}.\text{HUS\_SIETE}^{-0,823}$
Tt	0.985	$\text{Tt}=e^{-16,936}.\text{Faško}^{2,237}.\text{HUS\_SIETE}^{2,848}$
WHC	0.659	$\text{WHC}=e^{13,77}.\text{PR\_SKLON}^{-4,26}.\text{Kr}^{4,413}$
RFC	0.501	$\text{RFC}=e^{4,964}.\text{ZR\_MAX}^{-1,441}$
SFC	0.904	$\text{SFC}=e^{1,891}.\text{HUS\_SIETE}^{0,741}.\text{OR}^{-0,393}$
PK	0.736	$\text{PK}=e^{8,581}.\text{Kr}^{-0,849}.\text{Faško}^{-0,59}$
LPE	0.517	$\text{LPE}=e^{1,038}.\text{TEP\_REG}^{-0,923}$
Rech	0.894	$\text{Rech}=e^{2,757}.\text{HUS\_SIETE}^{-1,107}.\text{PR\_SKLON}^{-0,437}$
EMP	0.409	$\text{EMP}=e^{-1,866}.\text{OR}^{-0,577}$
K0	0.76	$\text{K0}=e^{-6,45}.\text{SNEH100}^{1,121}$
K1	0.778	$\text{K1}=e^{-3,134}.\text{TVAR\_POV}^{-0,562}.\text{SKLON\_HL}^{0,738}$
K2	0.903	$\text{K2}=e^{17,768}.\text{TVAR\_POV}^{-0,625}.\text{Faško}^{-3,071}$
LHZ	0.943	$\text{LHZ} =e^{-5,188}.\text{LES}^{1,4}.\text{ZR\_MAX}^{2,102}$

PER	0.933	$PER=e^{3,763}.F^{0,698}.TEP\_REG^{-3,091}$
MB	0.934	$MB=e^{1,377}.LES^{0,409}.tc\_KIR^{-0,543}$

Pooling group 3

Model parameter	**Multiple R**	**Regional Regression Formulae**
DDF	0.85	$DDF=e^{4,559}.LES^{0,857}.HG\_CHAR^{-0,808}$
Tt	0.86	$Tt=e^{-40,131}.LES^{-0,458}.HG\_CHAR^{7,808}$
WHC	0.52	$WHC=e^{-4,09}.F^{-0,147}$
RFC	0.777	$RFC=e^{-3,946}.LES^{2,193}.SNEH100^{0,616}$
SFC	0.806	$SFC=e^{-7,385}.SNEH100^{1,423}$
PK	0.847	$PK=e^{8,436}.SNEH100^{-1,186}.HG\_CHAR^{0,575}$
LPE	0.77	$LPE=e^{-8,181}.SNEH100^{1,485}$
Rech	0.921	$Rech=e^{3,823}.ODTOK\_31\text{-}80^{-1,057}$
EMP	0.706	$EMP=e^{-0,021}.HUS\_SIETE^{-3,347}.SKLON\_HL^{0,485}$
K0	0.646	$K0=e^{-3,352}.SNEH100^{1,12}.HG\_CHAR^{-0,624}$
K1	0.682	$K1=e^{-2,785}.TVAR\_POV^{-0,182}.Kr^{-0,53}$
K2	0.733	$K2=e^{-5,180}.ODTOK\_31\text{-}80^{0,718}$
LHZ	0.828	$LHZ=e^{-2,206}.TVAR\_POV^{0,33}.SNEH100^{1,299}$
PER	0.841	$PER=e^{2,466}.HUS\_SIETE^{-2,803}$
MB	0.841	$MB=e^{-0,761}.ODTOK\_31\text{-}80^{0,583}$

(For pooling group No1, the MB parameter was set 2.5 for all catchments.)

Validation of Regional Regression Formulae

To validate the derived formulae, all sub-catchments were considered as ungauged. Model parameter values were estimated using values of sub-catchment's physiographic characteristics. Although several formulae were derived for estimation of each of the model parameter, finally the one (with highest multiple coefficient of correlation -R) was selected to represent model parameter value

As an example Hronec – Čierny Hron (7045) sub-catchment was selected to validate the regional regression formulae derived for pooling group No.3. The comparison of results of runoff obtained by model calibration and using derived regional parameters is presented in (Fig.3).

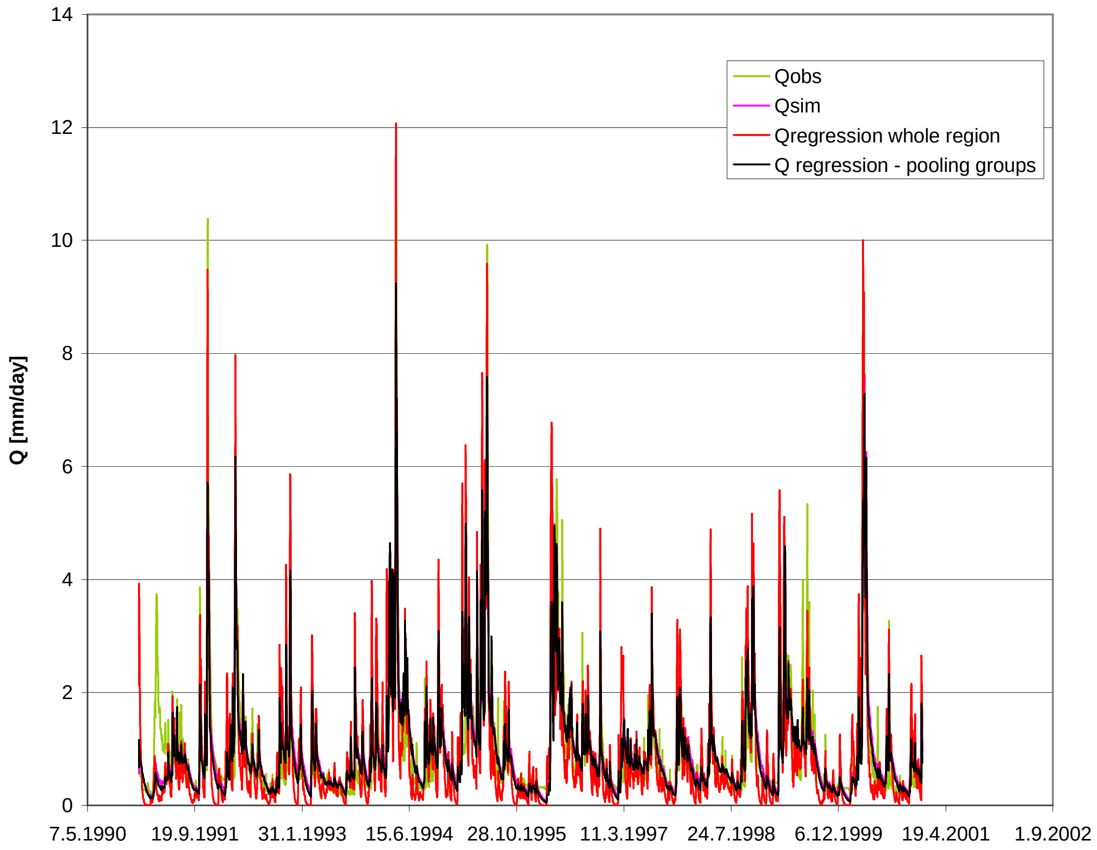

Fig. 3 Observed runoff, runoff obtained by model calibration and runoff obtained by regional regression formulae in Čierny Hron sub-catchment (7045).

Conclusions

In this paper a modification of regional model parameter estimation was tested on the Hron region of Slovakia. Subcatchments were grouped to pooling groups according selected physiographic characteristics by applying cluster analysis. Using multiple regression method, formulae for estimation of model parameters were derive for all pooling groups. The quality of the results was tested using Nash–Sucliffe objective function, which showed comparable results as by calibration of model parameters in subcatchments. The values of Nash–Sucliffe objective function were in average 0,5-0,6 for parameters derived for the whole region, and were slightly improved with average values 0,6-0,7 for parameters derived in selected pooling groups.

Finally we can conclude that the derived regional regression formulae for selected pooling groups can be considered as applicable for rainfall-runoff modeling in selected ungauged catchments in the Hron region of Slovakia.

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References

Burn, D. H. (1990): Cluster Analysis as applied to regional flood frequency, J. of Wat. Res. Plan. and Manag., 115, 5, 567-582.

Croke, B.F.W. and Norton, J.P., 2004. Regionalisation of rainfall-runoff models. In: Pahl-Wostl, C., Schmidt, S., Rizzoli, A.E. and Jakeman, A.J. (eds), Complexity and Integrated Resources Management, Transactions of the 2nd Biennial Meeting of the International Environmental Modelling and Software Society, iEMSs: Manno, Switzerland. ISBN 88-900787-1-5

Hartigan J.A., 1975. Clustering Algorithms. New York, John Wiley and Sons.
Hughes, D.A., Estimation of the parameters of an isolated event conceptual model from physical catchment characteristics. Hydrol. Sc. Journal 34(5), 539-557.1989.

Klemeš, V., 1986. Operational testing of hydrological simulation models. Hydrological Sciences Journal, 31: 13-24.

Kohnová, S., Zvolenský, M., Jazudek, V.: Odvodenie regionálnych regresných vzťahov pre odhad parametrov zrážkovo-odtokového modelu na povodiach bez priamych pozorovaní. Acta Hydrologica Slovaca, Vol. 5, 2, 2004, 251-257

Kohnová,S., Zvolenský, M., Hlavčová, K., Szolgay, J.: Odvodenie regionálnych regresných vzťahov pre odhad parametrov zrážkovo-odtokového modelu v povodí Hrona. Acta hydrologiaca Slovaca, Vol. 7, 1, 2006. v tlači

Kokkonen T. S., Jakeman A. J., Young P. C. and Koivusalo H. J., 2003. Predicting daily flows in ungauged catchments – model regionalization from catchment descriptors at the Coweeta Hydrologic Laboratory, North Carolina. Hydrological Processes

Kubeš, R., 2002.Uplatnenie zrážkovo-odtokového modelu pri simulácii extrémnych zrážkovo-odtokových situácií. 14 konferencia mladých hydrológov. Práce a štúdie 66, SHMU, Bratislava, p. 29–40.

Magette, W. L., Shanholtz, V. O., and Carr, J. C., 1976, ‘Estimating selected parameters for the Kentucky watershed model from watershed characteristics’, Water Resour. Res. 12(3), 472– 476.

Merz, R., Blöschl, G. 2004. Regionalisation of catchment model parameters. Journal of Hydrology 287: 95–123

Nathan, R.J., McMahon, T.A., 1990. Identification of homogenenous regions for the purposes of regionalisation. Journal of Hydrology, 121, p. 217-238

Servat, E. and Dezetter, A., 1993, ‘Rainfall-runoff modelling and water resources assessment in north-western Ivory Coast. Tentative extension to ungauged catchments’, J. Hydrol.148, 231– 248

Spate, J.M.; Croke, B.F.W.; Norton, J.P., 2004. A Proposed Rule-Discovery Scheme for Regionalisation of Rainfall-Runoff Characteristics in New South Wales, Australia. International Environmental Modelling and Software Society (iEMSs) Conference. “Complexity and Integrated Resource Management”

Ross, G.A., 1970. The Stanford watershed model: The correlation of parameter values selected by a computized procedure with measurable physical characteristics of the watershed. Research Report 35, Water Resources Institute, University of Kentucky, Lexington.

Vandewiele, G.L., Xu, C.-Y. and Huybrechts, W., 1991. Regionalisation of physically-based water balance models in Belgium, application to ungauged catchments. Water Resources Management 5: 199-208

Weeks, W. D. and Ashkanasy, N. M., 1983, ‘Regional parameters for the Sacramento Model: A case study’, Hydrology and Water Resources Symposium, Hobart.