INTERNATIONAL HYDROLOGICAL PROGRAMME

Monitoring and modelling catchment water quantity and quality

8th Conference of the European Network of Experimental and Representative Basins (ERB)
Ghent (Belgium), 27 – 29 September 2000

Convened by: ERB and UNESCO/IHP (FRIEND)

PROCEEDINGS

Edited by Niko Verhoest, Jim Hudson, Rudi Hoeben and François De Troch

IHP-VI | Technical Documents in Hydrology | No. 66
UNESCO, Paris, 2003

(SC-2003/WS/16)

Preface

The present volume is the edited set of proceedings of the conference ‘Monitoring and Modelling Catchment Water Quantity and Quality’, held at Ghent, Belgium, September 27-29, 2000. This conference was convened by the European Network of Experimental and Representative Basins (ERB) in conjunction with UNESCO (IHP FRIEND Project nr. 5). The ERB, which was founded in 1986, is an open member network promoting international cooperation of European institutes and research teams involved in hydrological studies of catchments. At the time of the conference, the network involved 14 member countries (Belgium, Czech Republic, Finland, France, Germany, Italy, The Netherlands, Poland, Romania, Russia, Slovakia, Spain, Switzerland and the United Kingdom). Exchange of information amongst the members is encouraged by means of biennial international conferences.

A very important aspect of hydrological science is the modelling of hydrological fluxes aiming at a better understanding of the physics behind it and also to use these models in a prediction mode for anticipating extreme events. Yet, models cannot be developed or improved without the availability of data. Therefore, monitoring programs and analysis of data form the profound basis for developing models. The conference created the possibility to join both aspects of the hydrological science. From the 65 contributions at the conference, 15 papers were selected based on a review process, and are presented in this volume. The editors wish to express their gratitude to the reviewers for their conscientious and thorough work.

The editors would like to dedicate this volume to Professor Václav Eliáš, International ERB Network coordinator, who died on January 9, 2002. Professor Eliáš was an enthusiastic and thoughtful person who tried to strengthen the coherence between the ERB members. His continuous encouragement to young scientists will remain in our thoughts forever.

Niko Verhoest
Laboratory of Hydrology and Water Management
Ghent University, Ghent, Belgium

Jim Hudson
CEH Wallingford
Wallingford, United Kingdom

Rudi Hoeben
Laboratory of Hydrology and Water Management
Ghent University, Ghent, Belgium

François De Troch
Laboratory of Hydrology and Water Management
Ghent University, Ghent, Belgium

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Groundwater flow modelling of three wetland ecosystems in river valleys in Flanders, Belgium

Batelaan, O., T. Asefa, P. Van Rossum & F. De Smedt

Department of Hydrology and Hydraulic Engineering, Free University of Brussels
Pleinlaan 2, 1050 Brussels, Belgium
Email: batelaan@vub.ac.be

ABSTRACT

Research in the ecology of wetlands is quite established. However, research in the hydrology of wetlands is much less developed. In Flanders, Belgium, a research project was initiated to investigate ecohydrological differences in wetlands. Three wetlands (Doode Bemde, Vorsdonkbos, and Zwarte Beek Valley) have been examined in detail. As these wetlands are predominantly fed by discharging groundwater, the groundwater flow to the wetlands is here investigated by way of modelling and the results discussed. A supra-regional groundwater model was developed, as well as three regional groundwater models. Together with particle tracking models, these models reveal the flow system characteristics of the wetlands. The results indicate the dependence and vulnerability of the wetlands with respect to their recharge area. The results also form the basis for further hydrochemical analysis of the wetland groundwater system.

1. INTRODUCTION

In Flanders, Belgium, restoration of wetland ecosystems in river valleys is receiving an increasing amount of attention. The study of evaluation tools for restoration scenarios has therefore become a point of priority within the framework of the Flemish governmental impulse program for nature conservation and development (VLINA). In one of the research projects, conducted within this program, the relationships between soil, water characteristics and nature quality (i.e. vegetational diversity) of three Flemish river basin wetlands were examined (Huybrechts *et al*., 2000). These wetlands were the Doode Bemde in the valley of the Dijle River, Vorsdonkbos in the valley of the Demer River, and Zwarte Beek Valley along the Zwarte Beek River, a tributary of the Demer River (Figure 1).

This paper presents the part of the project concerning the modelling of the groundwater flow to the wetlands under investigation, as these wetlands are predominantly fed by seepage groundwater. The characteristics of the groundwater system, together with the groundwater chemistry, are therefore the major controlling factors for the vegetation. Van Rossum *et al.* (2000) discuss the different groundwater quality characteristics, origins and hydrogeochemical evolutions of the groundwater within and around the wetlands.

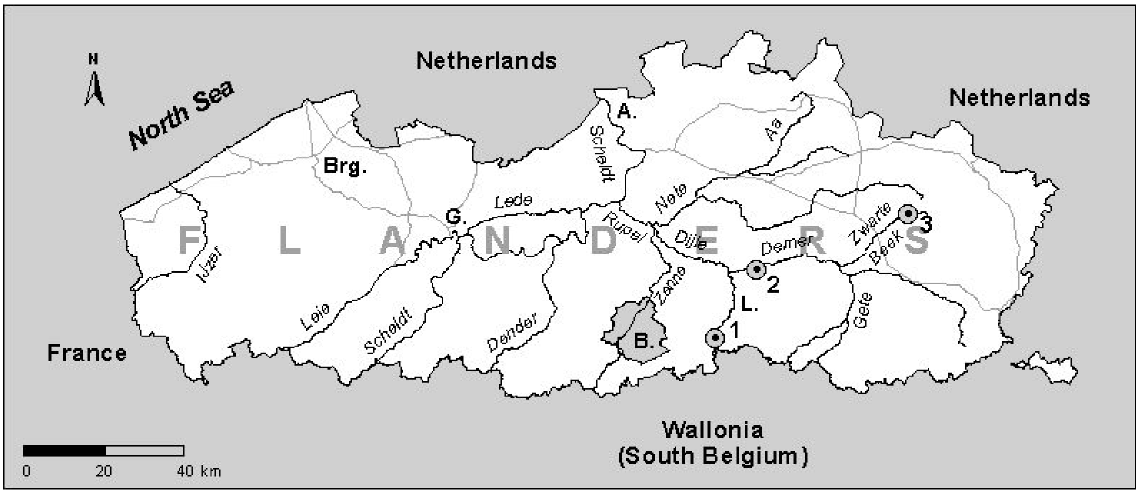

Figure 1: Location map of the three examined river basin wetland ecosystems. 1 = Doode Bemde, 2 = Vorsdonkbos, and 3 = Valley of the Zwarte Beek. B. = Brussels, A. = Antwerp, G. = Ghent, Brg. = Bruges, and L. = Louvain.

2. MODEL SETUP

The groundwater seepage in all three wetlands is sourced from recharge in the surrounding hills. Subsequently, it moves through sandy aquifers towards the wetlands. In the Doode Bemde these aquifers belong to the Brussels Formation (Eocene). In the Valley of the Zwarte Beek they belong to the Diest Formation (Miocene) and in the Vorsdonkbos to both.

Since the groundwater discharge to the study areas occurs with a fairly constant flux, the model is best setup as a steady state model. For the modelling of the three study areas it was necessary to set up realistic boundary conditions, heads or fluxes. There were insufficient measured piezometric heads in the surroundings of the study area available, nor were there any natural boundaries, such as rivers or water divides, to define boundary conditions. Therefore, ‘telescopic refinement’ has been used instead to obtain realistic boundary conditions. In the first instance a supra-regional model was applied, and on the basis of the calculated groundwater heads from this model the boundary conditions for the regional model were extracted.

For this study, the supra-regional model for the Nete, Demer and Dijle basins could be used (Batelaan *et al*., 1996) (Figure 2). This existing model was improved by calculating the actual spatially distributed recharge using the WetSpass modelling procedure (Batelaan & De Smedt, 2001). Since groundwater level is an input for the recharge estimation model, and recharge is an input to the groundwater model, the two models are coupled. Five iterations of the model couple (supra-regional model and WetSpass) were necessary to obtain a stable, steady-state solution. At every simulation of the groundwater model the most recently calculated recharge is used, and consequently the recharge is recalculated with an updated groundwater level. The calculated groundwater level in the supra-regional model had a spatial resolution of 50 m and was interpolated for the boundary conditions to 20 m for the regional model.

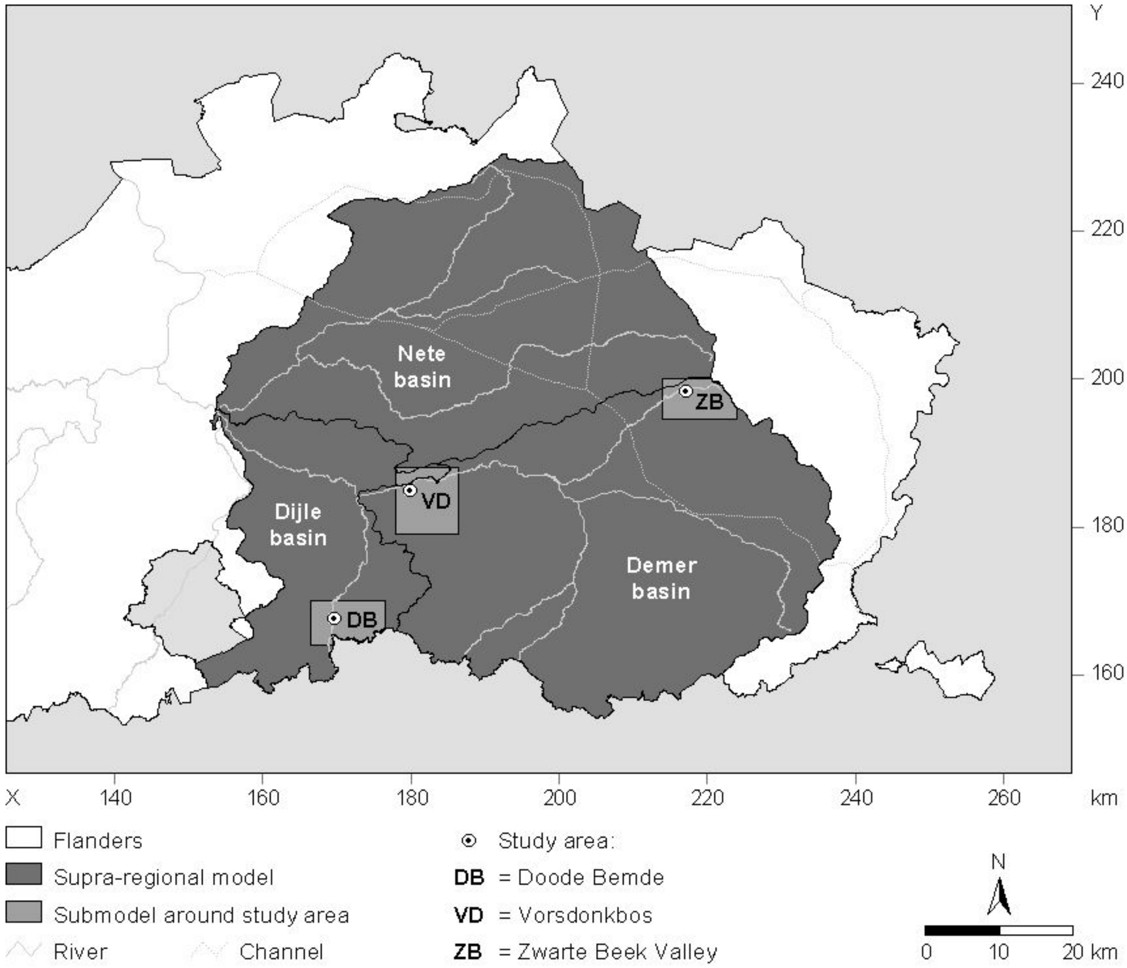

Figure 2: Nete, Demer and Dijle supra-regional model, with the three submodels.

In the Vorsdonkbos model a constant head is defined by the Demer River, just north of the study area. This head is calculated on the basis of the average measured river stage (1991-1997) of 9.8 m (TAW) in nearby Aarschot and an estimated water slope of 0.5 m km^{-1}. In addition, constant heads for the main river for the Dijle (Doode Bemde) and Zwarte Beek have been defined for use in the regional models.

The level at which the groundwater will seep at the land surface, in drainage ditches or wetlands is defined as the maximum seepage level. This level has been determined by way of an Arc/Info Topogridtool interpolation of the contour lines of 1:10 000 scale topographic maps. Locally, in the study area, measured topographic levels where also included in this interpolation, as well as a high resolution topographic database of the Demer valley obtained from aerial laser altimetry.

Average groundwater pumping rates have been determined for the three areas on the basis of pumping data for 1993-1995. Within the model areas of Doode Bemde, Vorsdonkbos and Zwarte Beek extractions of respectively 532, 7501 and 212 m^3d^{-1} were estimated.

3. MODELLING TOOLS

The USGS modular three-dimensional finite difference groundwater model, MODFLOW (Harbaugh & McDonald, 1996) has been used to simulate the groundwater flow.

MODFLOW’s DRAIN package has been used to simulate the groundwater discharge areas. The seepage surface has initially been set to topography minus 0.5 m. This value is assumed to represent the average field ditch depth, which drains the groundwater discharge. This value has been optimized for each regional model during calibration based on the extensive piezometer network within the study areas. The calibration resulted in a seepage level of 0.31, 0.25 and 0.50 m for Doode Bemde, Vorsdonkbos and Zwarte Beek respectively. These differences in seepage levels can be attributed to a different density of drainage ditches in each area. The mean absolute errors finally obtained for the calibration of the groundwater level in Doode Bemde, Vorsdonkbos and Zwarte Beek were respectively 0.33, 0.10 and 0.23 m.

MODPATH (Pollock, 1994) has been used to determine by particle tracking the recharge area and flow times. In order to determine the recharge areas as accurately as possible forward tracking was used from all potential recharge areas linked to the discharge areas of concern. Subsequently, by analyzing all the flow paths obtained, those ending in the groundwater seepage areas could be selected.

Table 1: Characteristic values for discharge, recharge area and flow times for the three study areas.

Study area	**Vorsdonkbos**	**Doode Bemde**	**Zwarte Beek**
Area [km^2]	0.25	0.21	0.26
Discharge area [km^2]	0.10 (40 %)	0.11 (52 %)	0.17 (64 %)
Average discharge [$mm\ d^{-1}$]	21.2	2.6	16.4
Recharge area[1] [km^2]	4.32	0.57	2.06
Ratio rech./dis. area	43.2	5.2	12.4
Average flow time [yr]	162	16	192
Maximum flow time [yr]	848	193	1634
% dis. younger 5 year	3.8	37.5	3.0
Average age discharge[2] [yr]	170	17	194

[1] *Exclusive groundwater discharge area*

[2] *Average flow time weighted by recharge flux*

4. RESULTS

Table 1 gives typical calculated values related to the groundwater system for the three study areas. The sizes of the study areas and the discharges occurring therein are very similar for the three areas. The average discharge however varies much more due to the strongly varying size of the recharge areas and the average flow times from recharge to discharge area. Compared to the other two areas, the size of the recharge area is very low for the Doode Bemde, resulting in a low groundwater discharge.

In Figure 3 (lower right), as an example for the three study areas, the calculated groundwater discharge area for Vorsdonkbos is given. This discharge map is compared in the figure to estimates of the groundwater discharge as indicated by phreatophytic vegetation (Figure 3, upper left), the zone with a measured maximum yearly groundwater level fluctuation of less than 0.6 m (Figure 3, upper right) and measured upward groundwater pressures. It can be observed from this figure that the groundwater discharge occurs mainly along the southern rim of the study area and in a north-south band, east of the centre of the study area.

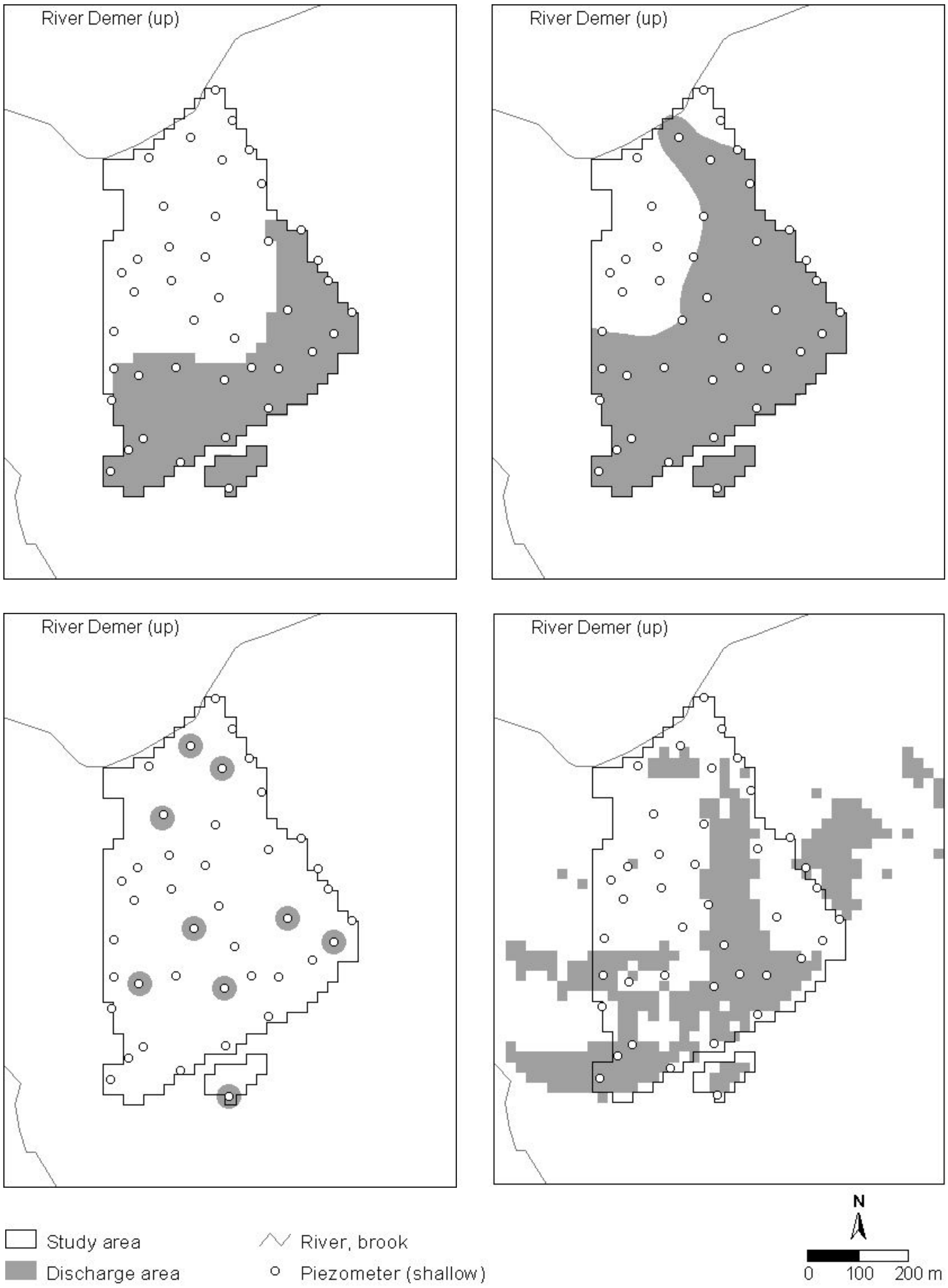

Figure 3: Modelled and measured groundwater discharge area for Vorsdonkbos, upper left: mapped phreatophytes indicating groundwater discharge, upper right: measured yearly groundwater level fluctuation less than 0.6 m, lower left: installed piezometer nest with piezometers measuring at two depths, indicating upward groundwater flow, lower right: groundwater model calculated groundwater discharge.

The total surface of groundwater discharge within the study area is 0.10 km^2, which means that 40 % of the study area receives permanent discharge. The discharge has an average flux of 21.1 mm d^{-1}. This flux is much greater than the flux in the Doode Bemde and slightly greater than in the valley of the Zwarte Beek.

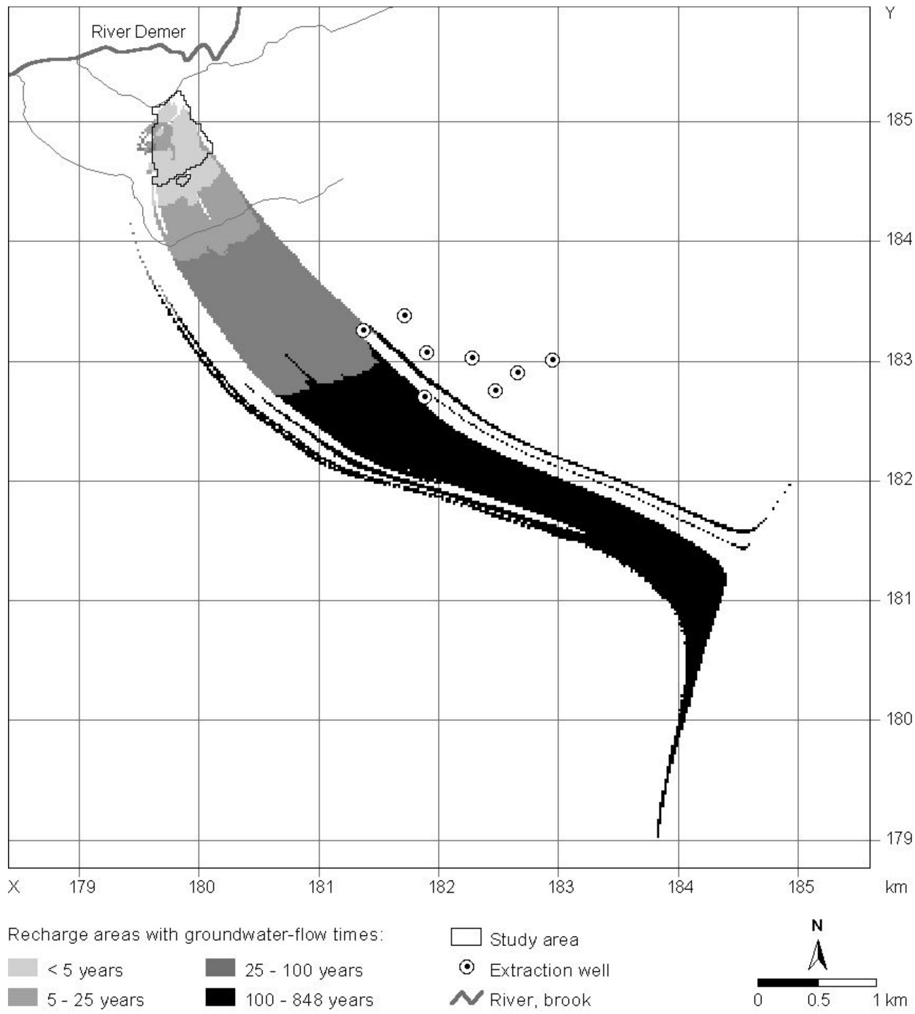

Figure 4: Simulated recharge areas and flow times to groundwater discharge areas of Vorsdonkbos.

Figure 4 gives the simulated recharge areas and flow times of the discharge areas within the study area of Vorsdonkbos. The recharge area extends up to 6 km in a south-easterly direction from the study area. The recharge area, excluding the discharge area itself, is 4.32 km^2, 43.2 times the area of discharge. This ratio of recharge to discharge area is much greater than in the other two study areas. At the north-eastern part of the recharge area the effect of some pumping wells can clearly be observed.

The average and maximum flow times to the discharge area in Vorsdonkbos are respectively 162 and 848 yr (Table 1). The average flow time is slightly shorter than in the valley of the Zwarte Beek, but much longer than in the Doode Bemde. The average age of the seeping groundwater in Vorsdonkbos, i.e. the average flow times weighted according to their recharge, is 170 yr. The spatial distribution of the recharge seems therefore to be quite uniform. The percentage of young groundwater (younger than 5 years) that is discharging in the study area is 3.8 %. This percentage is relatively low, which means that the area has a relatively low vulnerability with respect to water quality deterioration.

5. CONCLUSIONS

A groundwater flow modelling procedure for wetlands was introduced and applied to three wetland ecosystems in river valleys in Flanders. The size of the wetlands and the discharge zones within it are similar. However, the discharge intensity is quite different, as well as the recharge area and the flow times. The results indicate the vulnerability of the wetlands with respect to their hydrological system and the importance of groundwater systems analysis for the protection and re-development of wetlands.

ACKNOWLEDGEMENT

This study has been financially supported by the Flemish Administration, VLINA project C96/03.

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Assessment of the relation between the NAM rainfall-runoff model parameters and the physical catchment properties

Celleri, R.[1], L. Timbe[1], R.F. Vázquez[2] & J. Feyen[2]

[1] *Universidad de Cuenca, PROMAS*
Casilla 01.01.168, Cuenca, Ecuador
[2] *K.U.Leuven, Institute for Land and Water Management*
Vital Decosterstraat 102, 3000 Leuven, Belgium
Email: raulito_vz@yahoo.com

ABSTRACT

The NAM module of the MIKE-11 code was applied to four Belgian Catchments with the intention of finding relationships between model parameters and physical catchment descriptors (PCD). Ten NAM module parameters (NMP) out of the maximum set of 15 parameters were used since the irrigation and snowmelt components were not considered. Model calibration was performed using hydrological time series of 7 to 12 years, finding a good agreement between observed and simulated discharges. Of the 10 NMP, 9 were found to be statistically independent. Only 12 PCD exhibited independence out of a total of 27 considered. The relationships between the retained 9 NMP and 12 PCD were studied finding high correlation coefficients between them. Only three relationships (U_{max}, $CK_{1,2}$ and C_{area}) were found statistically significant, and the drainage density was found to be the most important PCD. The authors recommend validating the derived relationships before using them in a predictive context.

1. INTRODUCTION

Conceptual rainfall-runoff models have been widely used to simulate runoff generation processes. These models do not explicitly take into account the spatial variability of inputs, outputs, or parameters and for this reason they are usually structured to utilize average values of the catchment characteristics. Due to this fact, model parameters usually do not account for physical properties of the basins and, in consequence, they have to be assessed by model calibration. Another approach for the determination of parameter values is to establish the relationship between parameter values and catchment characteristics. Given that a relation exists between the physical catchment descriptors (PCD) and the model parameters (MP), the great advantage of such an approach is that ungauged catchments can be analyzed as well (Vandewiele *et al.,* 1991). Many of the early studies aimed to estimate event characteristics with the main focus on flood indices such as the mean annual flood or on flood frequency, low flows and mean annual runoff. Some examples can be found in Mosley *et al*. (1993). More recently, emphasis has been put on the estimation of the water balance model parameters aiming at the simulation of continuous records with the potential for the reconstruction/estimation of daily/hourly flow records (Sefton *et al*., 1998; Rawdan *et al.,* 1999). Seibert (1999) applied the HBV model to 11 catchments within the NOPLEX area (central Sweden) trying to relate MPs to PCD. Relationships for six of the 13 MP could be established but some relations put the physical basis of the model into question since physical processes could not explain them. Sefton & Howarth (1998) found relationships amongst parameters of the IHACRES model and various PCD. In that case 60 catchments in England and Wales were studied and 10 morphometric variables, five soils descriptors, eight land use types and seven climate variables analyzed. Relationships were determined by multiple linear regressions and for some predictive equations log-transformations on all the variables were used before performing the analysis.

The objective of the present research was to obtain a set of PCD of four medium sized Belgian basins and to examine if these physical descriptors could be directly related to the NMP. The existence of such relationships would allow the model to simulate runoff in ungauged catchments within the region and would make it possible to address the physical basis of the model as relationships could be expected from physical reasoning. Basins of the rivers Gete, Jeker, Nete and Ourthe, with surface areas ranging between 300 and 600 km^2, were chosen due to the variability in catchment properties, representing different topographic and geomorphologic conditions. As a result of data constraints, model calibrations were performed using daily values of rainfall, evapotranspiration and runoff.

2. THEORY AND METHODS

In the NAM module, physical processes are simulated according to their mathematical conceptualization; therefore relationships between model parameters and catchment descriptors could be feasible. If such relationships could be previously determined, NMP could be easily interpolated and discharge series produced. In this case the methodology involved three distinct stages: i) a set of PCD, lumped to the catchment scale, was assembled using GIS; ii) the calibration of the NAM model was performed for every basin and iii) the relationships between NMP and PCD were derived and evaluated.

2.1. Physical catchment descriptors (PCD)

The first step was to find adequate PCD that could be useful for a comparison with MP. Distinction is made between PCD of catchment form and PCD of catchment relief (Linsley *et al*., 1982). In this research the focus was centred on geomorphologic variables that could be useful for estimating hydrologic parameters. Description of the physical features of catchments was thereby in general based on morphological indices, percentage coverage of soil types, percentage coverage of land use types and climatic indices. Land use was classified in five groups according to the CORINE Land Cover project, but using only the first level of the classification. Soils were divided into five groups as well, according to the Belgian textural classification. Mean annual rainfall was chosen as the main climate index. In this way a set of 27 descriptors was assembled (see Table 1).

2.2. The MIKE 11 NAM module

The NAM module (DHI, 1999) of the MIKE-11 code (Havnø *et al*., 1995) was used for the rainfall-runoff simulation. It performs the simulation by accounting for water content in four different and mutually interrelated reservoirs that represent physical elements of the catchment, namely surface, root zone, groundwater and snow storage. Irrigation and groundwater pumping can be considered additionally. The NAM module is defined as a deterministic and conceptual model, representing a simplified imitation of the land phase of the hydrologic cycle. As the NAM model is lumped it treats the catchment as a simple unit, with its parameters representing average values for the entire catchment.

Table 1: Physical Catchment Descriptors (PCD).

PCD	Symbol	Unit
Morphometric		
Mainstream length	Lm	[km]
Total channel length	Lt	[km]
Basin area	A	[km^2]
Basin perimeter	Pb	[km]
Basin length	Lb	[km]
Drainage density	D	[$km\ km^{-2}$]
Length of overland flow	L	[km]
Basin shape	Rf	[-]
N	n	[-]
Elongation	E	[-]
Circularity	Ec	[-]
Channel slope	sc	[$m\ km^{-1}$]
Land slope	sL	[%]
Relief	Hb	[m]
Relief ratio	R	[-]
Mean Elevation	h	[m]

PCD	Symbol	Unit
Land use		
Artificial surfaces	ARTS	[%] of area
Agricultural areas	AGRI	[%] of area
Forest and semi-natural areas	FRST	[%] of area
Wetlands	WLND	[%] of area
Water bodies	WBDS	[%] of area
Soil type		
Sandy	Sdy	[%] of area
Loamy	Lmy	[%] of area
Stony loam	Stl	[%] of area
Clay	Cly	[%] of area
Sandy loam	Sdl	[%] of area
Climate indices		
Mean annual rainfall	rain	[mm]

2.3. Calibration and evaluation

Input data for the NAM module consists of time series of daily rainfall, runoff and potential evapotranspiration. Parameters were found by model calibration against the time series of average daily hydrologic records at the outlet of the catchments. The study catchments were not split into subcatchments for the following two main reasons: i) the lack of runoff data in affluent streams and ii) to avoid the incorporation of channel routing parameters and their respective calibration. Refsgaard (1997) concluded that the split-sample test is sufficient to obtain a reliable calibration and evaluation for lumped models and that those models in general are not appropriate for the simulation of distributed variables, such as groundwater tables. Following that, calibration and evaluation of NAM was carried out using a traditional split-sample test. Two major steps were taken, namely i) automatic and ii) manual calibration (DHI, 1999). The automatic calibration is used to speed up the calibration process and to limit and constrain the most important parameters to a certain range of acceptable values. The automatic calibration routine is based on a multi-objective optimization strategy in which four different objectives can be optimized simultaneously. The routine uses the overall volume error (agreement between the average simulated and observed runoff), the overall root mean square error (RMSE) that depicts the agreement of the shape of the hydrograph, the average RMSE of peak flow events and the RMSE of low flow events.

Then, in the manual (stepwise) calibration, a trial and error parameter adjustment was made until satisfactory results were obtained. The stepwise-calibration strategy considers the different rainfall-runoff process descriptions for calibration of the parameters that mostly affect that process being described. The first step in the stepwise-calibration was to adjust the overall water balance, by adjusting the balance between the evapotranspiration and the difference between net precipitation and the runoff. Evapotranspiration would increase when increasing the maximum water contents in the surface storage U_{max} and the root zone storage L_{max}, and vice versa. Usually this is adjusted implicitly but the same result could be achieved explicitly by controlling the water balance output. This can be generated after each run of the model in order to evaluate the progress in the balance. The second step was to adjust the hydrograph shape of the peak runoff events. Peak volume adjustment, controlling the overland flow runoff coefficient (CQ_{OF}) and the time constant in the runoff routing ($CK_{1,2}$) accomplished this, respectively. This step was mainly applied to winter peaks, as winter peaks are much larger and more representative than summer peaks. The third step was to adjust the baseflow, mainly using the baseflow time constant (CK_{BF}). If the baseflow recession changes to a slower recession after a certain time, a lower groundwater reservoir should be added, including calibration of the recharge to lower groundwater storage CQ_{low} and the time constant for routing lower baseflow CK_{low}.

Table 2: The main NAM parameters (NMP).

NMP	Unit	Usual value	Definition
U_{max}	[mm]	10-25	Maximum content of surface storage (affects evaporation and small peaks)
L_{max}	[mm]	50-250	Maximum content of root zone storage (affects evaporation and water balance)
CQ_{OF}	[-]	0.01-0.99	Overland flow coefficient (divides excess rainfall into runoff and infiltration)
CK_{IF}	[h]	500-1000	Time constant for interflow (determines the amount of interflow together with U_{max})
TOF	[-]	0.0-0.7	Root zone threshold value for overland flow (delays overland flow at the start of the wet season)
TIF	[-]	0.0-099	Root zone threshold value for interflow (has the same effect for interflow as T_{OF} has for overland flow)
TG	[-]	0.0-0.7	Root zone threshold value for recharge (delays the groundwater recharge at the start of the wet season)
CKBF	[h]	500-5000	Time constant for routing baseflow (determines the shape of baseflow hydrograph)
$CK_{1,2}$	[h]	3-48	Time constant for routing overland flow (determines shape of peaks)
C_{area}	[-]	-	Ratio of groundwater catchment to topographical area (stands for drainage to or from neighbouring catchments)

A total of 10 NMP were calibrated without considering the irrigation and snow modules. Table 2 gives a summary of the main model parameters and their impact on the different components of the hydrologic cycle. For the quantitative assessment of the model performance with respect to the overall water balance error and the overall shape of the hydrograph, as in related research (Feyen *et al*., 2000; Vázquez & Feyen, 2002) use was made of the Nash & Sutcliffe (1970) coefficient of efficiency (EF). For calibration, EF-values higher than 0.76 were obtained, while for the evaluation period, values were higher than 0.73. The length of the period of simulation ranged between 10 and 12 years with exception of the Ourthe catchment for which the available data record was 7 years. As for similar research carried out in the past aiming to estimate the hydrologic behaviour from physiographic and climatic catchment attributes, in this study the multiple regression analysis technique was also used. Data were collated for a dependent variable and one or more independent or explanatory variables and statistical calculations were used to derive an equation relating variations in the dependent variable to values of the independent variables (Beven, 1997).

3. MATERIALS

Rainfall-runoff processes were analyzed on a daily basis. The Thiessen Polygon Method was used for the calculation of the lumped precipitation. In this case the normal-ratio method (Linsley *et al*., 1982) was used to bridge data gaps. Potential evapotranspiration was estimated as described in Feyen *et al*. (2000) and Vázquez & Feyen (2002). Digital terrain models (DTM) were produced from point elevation data. Firstly a triangular irregular network (TIN) was produced and from it a grid (LATTICE) was created. Digital maps of the river network, the land use and the soil type were also used.

Table 3: Statistics of the key PCD.

PCD	Mean	STD error	STD	Maximum	Minimum	Skewness
A	438.85	51.3	114.6	585.8	319.6	0.591
Rain	855.33	58.5	130.8	1046.7	756.7	1.713
D	1.034	0.2	0.4	1.5	0.5	-0.169
sL	3.356	1.3	2.9	7.6	0.8	1.565
ARTS	16.44	4.2	9.4	26.4	4.7	-0.447
AGRI	64.40	8.9	19.9	85.0	45.2	0.067
FRST	18.34	9.5	21.3	45.2	1.2	0.665
WLND	0.33	0.2	0.4	0.9	0.0	0.86
Sdy	18.98	14.4	32.1	66.8	0.2	1.93
Lmy	45.63	22.8	50.9	91.7	0.7	0.004
Stl	24.69	19.7	44.1	90.8	1.3	1.99
CSl	10.70	5.7	12.6	29.0	0.0	1.587

Legend: A = basin area, Rain = mean annual rainfall, D = drainage density, sL = land slope, ARTS = artificial surfaces, AGRI = agricultural areas, FRST = forest and semi-natural areas, WLND = wetlands, Sdy = sandy soil, Lmy = loamy soil, Stl = stony loam soil, CSl = clay + sandy loam soils

4. RESULTS AND DISCUSSION

Preliminary analysis involved investigation into correlation within the PCD and NMP data sets to identify possible interdependencies. When analyzing the set of 27 PCD a very high correlation was found between some of them; the reason for this situation is that for their calculation use was made of the same catchment characteristic or a previously calculated PCD. This enabled a reduction to just 12 PCD for the next analyses, choosing those which were determined only from the catchment characteristics and were particularly more meaningful from the physical point of view. The statistics of key PCD can be seen in Table 3. For the NMP the only significant correlation found was between TOF and CQ_{OF} with a determination coefficient large enough (0.9978) to support the relationship: CQ_{OF} = 0.6422 TOF + 0.0465. As a consequence of this, the number of NMP could be reduced to nine. The next step in the analysis consisted in finding a correlation between the key PCD and NMP. Each NMP was analyzed not only from a statistical point of view but also from a physical one, attempting to give a hydrologic meaning to each of them. For each NMP the PCD suggested by the correlation and those anticipated as relevant based on knowledge of hydrologic processes were summarized and can be found in Table 4. They are presented in decreasing order of significance, in terms of the regression coefficient, from left to right.

Table 4: Ranking of the PCD for each of the studied NMP.

NMP		**PCD**	
	1	**2**	**3**
U_{max}	sL	ARTS	Stl
L_{max}	CSl	sL	Rain
CKIF	A	AGRI	Lmy
$CK_{1,2}$	D	Lmy	FRST
TOF	Stl	D	FRST
TIF	Sdy	CSl	WLND
TG	Rain	Stl	sL
CKBF	D	FRST	Stl
C_{area}	D	Lmy	FRST

Relationships between NMP and PCD were determined applying a multiple linear regression technique. The small number of catchments made it impossible to perform a multiple regression analysis with more than two PCD as independent variables in order to avoid leaving zero degrees of freedom. Even for two PCD the situation is at its limit, and for this reason high determination coefficients were found ($R^2 > 0.82$). These relationships are listed in Table 5. After an inspection it was noticed that only 10 PCD were relevant in the relationships, with the drainage density D the most important one. None of the relationships had a physical basis.

Table 5: Multiple regression between the retained 9 NMP and the 10 main PCD.

Relationship	R^2
U_{max} = 10.931 + 1.333 sL – 0.2465 ARTS	0.999
L_{max} = 194.87 + 13.314 sL – 4.316 CSl	0.873
CKIF = -2812 + 9.8 A – 6.737 Lmy	0.871
$CK_{1,2}$ = -29.24 + 86.53 D – 1.18 FRST	0.998
TOF = -0.212 + 0.478 D + 0.00486 Stl	0.967
TIF = 0.9 – 0.00689 Sdy – 0.015 CSl	0.964
TG = -1.898 + 0.0024 Rain + 0.037 sL	0.996
CKBF = 17119.2 – 12140 D + 127.73 FRST	0.826
C_{area} = 0.376 + 0.415 D – 0.00197 Lmy	0.999

The final analysis consisted in using the F statistic to determine whether these results, with high determination coefficients, occurred by chance. Only the relationships for U_{max}, $CK_{1,2}$ and C_{area} were found statistically significant with a 5% probability and therefore their regression equations may be considered as meaningful for predicting the assessed value. This means that the six remaining relationships seem to occur by chance, which is mainly due to the small set of catchments in the analysis.

5. CONCLUSIONS

A set of four catchments was studied with the objective of deriving relationships relating PCD and NMP. After a preliminary analysis within the set of NMP, a significant correlation between TOF and CQ_{OF} was determined that was strong enough to support a linear relationship. A large number of PCD was disregarded from the study after finding them to have a strong correlation with key PCD since they had been calculated from the same basic physical characteristic or from a previously calculated PCD. Only 12 PCD were retained in the analysis. Hydrologic feasibility and statistical significance were the objectives for the formulation of the relationships but the complexity and lumping of processes represented in the empirical equations and model parameters, in addition to the small number of catchments studied, made it impossible to give physical significance to the final relationships. As a direct consequence of the small number of catchments that were analyzed, high correlation coefficients between NMP and key PCD were found, some of them without physical meaning or logical explanation. This problem also influenced the multiple linear regressions, since the number of involved variables had to be a maximum of two to avoid having zero degrees of freedom. The drainage density D of the catchment was the most important physical descriptor present in four relationships. When performing F statistics it was noticed that only three relationships (U_{max}, $CK_{1,2}$ and C_{area}) out of nine had statistical significance at the 5% level.

Nevertheless, the study can be considered as a first approach to the estimation of the NMP of medium sized Belgian catchments based on PCD. It has still to be seen whether these relationships are valid for a set of catchments, the physical characteristics of which are within the studied range, via evaluation and sensitivity analysis. Care must be taken when using these relationships especially when the catchment being analyzed has physical descriptors out of the given range. More catchments will have to be added to this study before finding reliable relationships for different scenarios and physical conditions.

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Calibration of a stochastic rainfall model based on a 100 year 10-minute rainfall time series

De Jongh, I., N.E.C. Verhoest & F.P. De Troch

Laboratory of Hydrology and Water Management, Ghent University
Coupure links 653, 9000 Ghent, Belgium
Email: Inge.DeJongh@rug.ac.be

ABSTRACT

A stochastic rainfall generator based on the modified Bartlett-Lewis rectangular pulses model (Rodriguez-Iturbe *et al*., 1988) was developed. This model was calibrated and validated using a 100 year 10-minute rainfall time series for Uccle (Belgium). The generator performs very well over a wide range of aggregation levels in reproducing the first and second order moments and the Zero Depth Probability, but it seems to fail in modelling short time heavy rainfall events. The internal structure of simulated rain storms is very similar to the structure of historical storms, but the time between independent rain events is underestimated during the simulation.

1. INTRODUCTION

Most hydrological and hydraulic modelling requires the input of rainfall data. Depending on the aim of the model, different types of rainfall series can be chosen. For certain applications, measured historical rainfall will be used as an input, while other applications require representative storms with a certain return period. A rainfall generator that is able to simulate long rainfall time series is an ideal basis from which to select representative storms.

Over the last few decades, many stochastic rainfall models have been developed. The first models were based on Markovian processes and were very simple, but could not predict the correct rainfall structure. By introducing more parameters the models performed better, especially when it became possible to cluster rainfall events. Rodriguez-Iturbe *et al*. (1987, 1988) studied in detail the characteristics of two cluster based models, the Neyman-Scott (NS) Rectangular Pulses model and the Bartlett-Lewis Rectangular Pulses model (BL). They found that both models were able to generate rainfall series with similar statistic characteristics as for the historical rainfall data for different aggregation levels, without having to change the parameter set. Yet it was found that the models underestimate the Zero Depth Probability (ZDP), i.e. the chance that no rain will occur in a certain time interval. Therefore, a correction of the BL and the NS models was made by Rodriguez-Iturbe *et al.* (1988) and Entekhabi *et al.* (1989), respectively.

This Modified Bartlett-Lewis model (MBL) has already given promising results according to Verhoest *et al.* (1997), who found that the model could generate the rainfall at Uccle (Belgium) well when the parameterization was based on a 27 year time series of rainfall. This paper describes the results of the calibration of the MBL, using a 100 year 10-minutes rainfall time series.

2. METHODS

The complete analytical structure of the stochastic model used in this study, the Modified Bartlett-Lewis Rectangular Pulses model (MBL), can be found in Rodriguez-Iturbe *et al.* (1988). Six stochastic parameters have to be estimated during the calibration of the MBL model by using the statistics of the historical time series. In our study, we used a 100 year 10-minute rainfall time series observed at Uccle (Belgium) that had been digitized by the Belgian Royal Meteorological Institute (RMI). As the climate of Belgium is seasonal, with mainly convective rain events in summer and cyclonic rainfall events in winter, the rainfall series of Uccle is not stationary. Therefore, the whole time series has been split up by the different months of the year, and for every month a parameter set will be determined.

Stochastic rainfall models, like the MBL, should return the basic structure of rainfall for different aggregation levels. In order to validate this, the first and second order moments together with the ZDP will be calculated for 6 aggregation levels (i.e. 10 min, 30 min, 1 hour, 6 hours, 12 hours and 24 hours) and cross examined with the historical statistics.

For the calibration of the 6 MBL parameters the method of moments or the method of maximum likelihood can be applied. Because the method of moments gives simple expressions (Burlando & Rosso, 1993), this method will be applied here. The ultimate goal is to estimate the parameter vector Θ :

$$\Theta = \left[\mathrm{X}_1, \mathrm{X}_2, \mathrm{X}_3, \ldots \right] \tag{1}$$

for which X_i represents a parameter of the MBL model. Suppose $F' = \left[F_1', F_2', \ldots \right]$, a vector of estimated statistics of different aggregation levels. The function $F(\Theta) = \left[F_1(\Theta), F_2(\Theta), \ldots \right]$ contains the statistics calculated from the analytical expressions for the same characteristics, based on the parameter vector Θ. Then it is necessary to find an estimation F':

$$F(\Theta) - F' = 0 \tag{2}$$

with 0 the null vector. It is obvious that this non-linear system is very complex and that the solution is not very simple. The multivariable Newton-Raphson solution for a set of non-linear equations cannot be used because this system does not converge. The alternative solution to estimate Θ is to minimize of the sum of squares of the residuals, which have to be normalized first, because the different components have different ranges:

$$Z_{\min} = \min \left[\left(1 - \frac{F_1(\Theta)}{F_1} \right)^2 + \left(1 - \frac{F_2(\Theta)}{F_2} \right)^2 + \ldots + \left(1 - \frac{F_i(\Theta)}{F_i} \right)^2 + \ldots \right] \tag{3}$$

For the minimization of this function the 'Powell's Quadratically Convergent Method' (Press *et al*., 1986) can be used.

Once the parameters are estimated using a historical time series, the analytical moments for all the aggregation levels can be calculated using theoretical expressions for the first and second order characteristics. A comparison of the historical and analytical moments is used for a validation of the retrieved parameter set for every month. Once the optimal parameter sets are retained, the rainfall model can be used to generate a long time series of rainfall, for example 1000 years of 10-minute rainfall.

On the simulated rainfall time series, different statistical tools can be used to further validate the model. As extreme rainfall events are important for the hydrological modeller, a frequency analysis of extreme events will give important information about the usefulness of the generated time series in hydrological modelling. The intensity-duration-frequency (IDF) curves define the relation between the return period of extreme values for an aggregation level and its intensity. By comparing the IDF-curves of the historical time series and those of the simulated rainfall time series, we can check whether the rainfall model can generate the extreme values and their distribution in time in an accurate way.

As it is important to keep the observed time distribution of rainfall intensity in heavy storms while simulating a rainfall time series, the agreement in internal storm characteristics between the historical and the simulated storms has to be checked. Huff (1967) developed probability relations for the distribution of rainfall during a storm event for the state of Illinois (USA) to supply quantitative information about the intrastorm variability. These relations are called mass curves and give the relative cumulative rainfall as a function of the relative time that has passed since the beginning of the event. The mass curves for both the historical and simulated rainfall time series for Uccle can be calculated and compared with each other. As a result, storms are defined as independent if they are separated by a period of more than 24 hours with no rain. The storms are subdivided in four groups, depending on whether the largest amount of rain fell in the first, the second, the third or the fourth quartile of the storm. For every selected storm in a given quartile, a frequency analysis is performed on the cumulative rainfall for each 5% time interval, resulting in probability levels for the cumulative rainfall intensity. The mass curves are constructed by connecting the values with the same probability level of the different time intervals. The interstorm relations are studied using the time lag between 2 independent rain events. The methodology used in this study is based on the theory by Restrepo-Poseda & Eagleson (1982) and will not be repeated here in this paper. The results obtained, i.e. the number of hours between two independent storms, are compared for the historical and simulated time series.

3. RESULTS

After a process of trial and error, final parameter sets were derived for every month of the year. By comparing the historical and simulated moments and the ZDP values (Figure 1), we find that the generated rainfall time series simulates very well the values of the first, the second order moments and the ZDP values. The IDF-curves for several return periods and for every month separately are found using regressions in the frequency analysis for the different aggregation levels (10 minutes to 24 hours). A systematic underestimation of extreme values for small aggregation levels can be noticed (Figure 2). Only the curves obtained for January are given, but for the other months the same results are obtained. For larger aggregation levels, the simulated extremes have the same frequency as the historical ones.

Information about the intrastorm distribution of rainfall can be determined from the mass curves. The mass curves for the historical and the simulated time series are quite similar for all the probability levels and for all months. From Figure 3 it is obvious that the rainfall generator is able to keep the internal distribution of rainfall in independent storms. Finally, the interstorm relations are checked by comparing the time lag between 2 independent storms for the historical and simulated rainfall time series (Table 1). Good results are obtained for the month of May only, while the time lag calculated for the other months in the historical time series differs by several hours from the time lag between independent rainfall events in the simulated series.

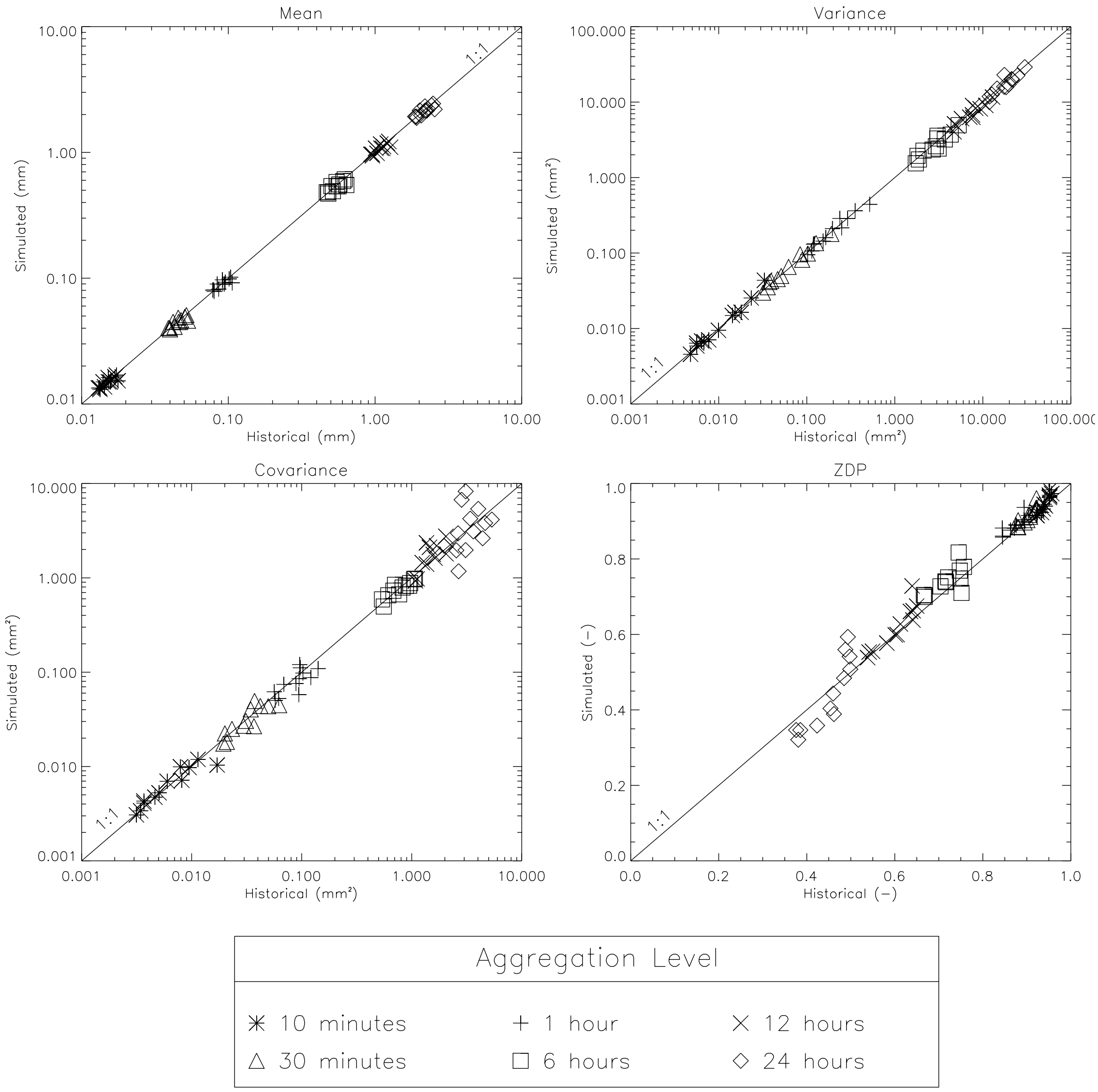

Figure 1: Comparison between the simulated and historical first and second order moments and the ZDP.

Table 1: The time lag between 2 independent rain events for the historical and the simulated rainfall series.

Month	Uccle	Simulated	Month	Uccle	Simulated
January	14h54	0h53	July	18h18	6h51
February	13h05	0h49	August	18h03	4h10
March	17h51	1h45	September	14h10	3h21
April	16h24	1h29	October	15h12	2h40
May	15h29	20h05	November	9h09	1h37
June	14h23	9h00	December	11h19	1h35

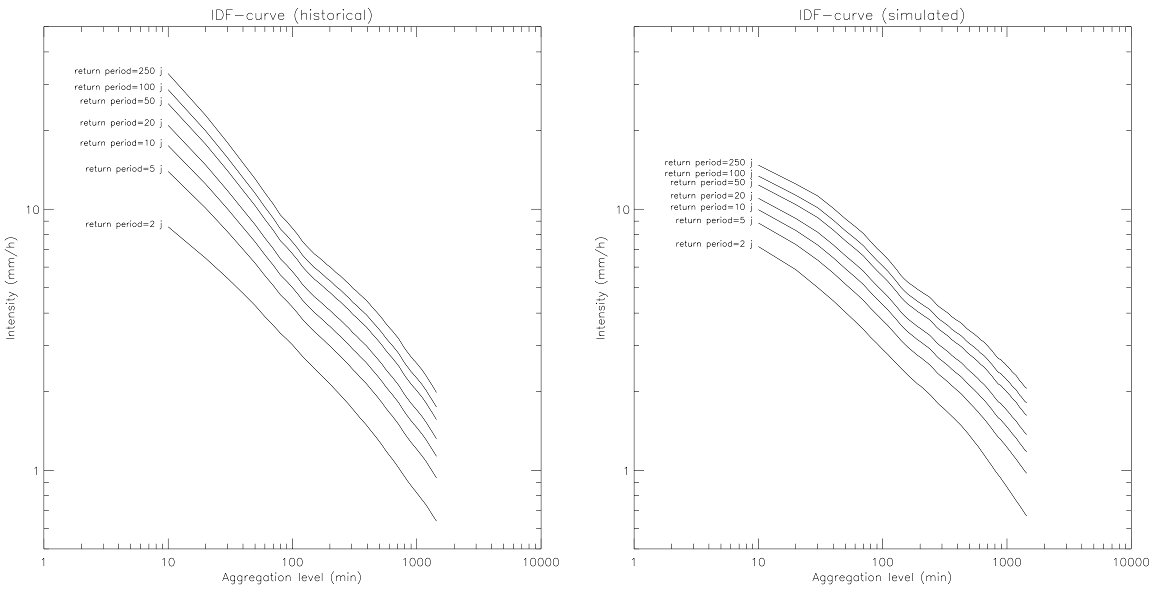

Figure 2: IDF-curves for January using the historical and simulated rainfall time series.

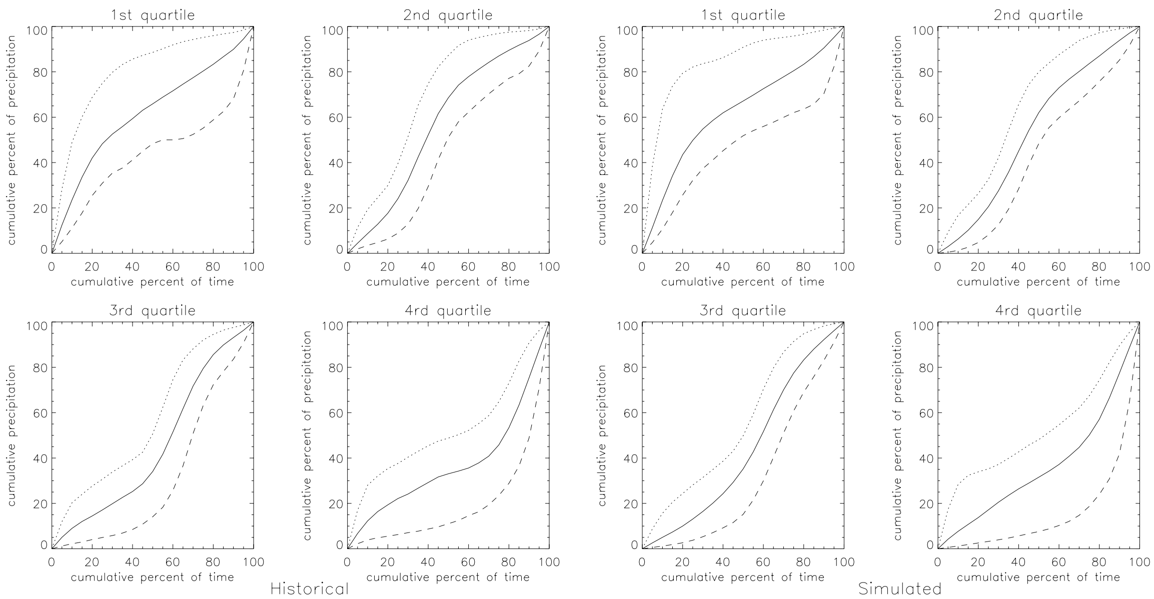

Figure 3: Comparison of the mass curves of the historical and simulated series for January with different probability levels: 10% (dotted line), 50% (full line) and 90% (dashed line).

4. CONCLUSIONS

The calibrated generator performs very well over a wide range of aggregation levels in producing the first and second order moments and the ZDP. However, the generator seems to fail in reproducing short time heavy rainfall events as can be seen from the IDF-curves. The time distribution of the rainfall within a storm compares well to the actual temporal rainfall pat-terns, although there are large differences found for the time lag between 2 independent storm events for the historical and simulated rainfall time series. We can therefore conclude that the processes on which the existing model is built are too simple to be able to model the complexity of the real rainfall patterns. In the future, extra processes will have to be added to the existing stochastic model, which will probably result in better simulated time series, but will make the parameterization a lot more complex and time consuming.

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Groundwater flow and nitrate migration; future developments

Dijksma, R.[1], H.A.J. Van Lanen[1] & M. Klopnowski[2]

[1] *Sub-department of Water Resources, Wageningen University*
Nieuwe Kanaal 11, 6709 PA Wageningen, the Netherlands
[2] *Polish Geological Institute, Lower Silesian Branch*
al. Jawarowa 19, 53-122 Wrocław, Poland

ABSTRACT

Intensification of agriculture has resulted in significant nitrate leaching in the Netherlands, threatening fresh groundwater bodies. Environmental laws have been imposed on farmers in order to reduce nitrogen application and losses. In the Noor basin, in the south-eastern part of the Netherlands, water flow and nitrate concentrations in ground- and surface water have been monitored. The flow and solute transport model FLONET/TRANS was used to calculate future nitrate concentrations. The historical nitrate input has been calculated for different land use types for the period 1950-1995. Future trends were simulated for the period 1998-2098. Three scenarios, reflecting reduction of the NO_3^- input at the phreatic water table by 25, 50 and 75% respectively, were compared. A reduction of the nitrate input by 25% still results in an increase in the nitrate concentration of ground- and surface water. A decrease of 75% results in slowly decreasing nitrate concentrations.

1. INTRODUCTION

Since the 1950’s, intensification of agriculture in the Netherlands has resulted in significant nitrate leaching to the groundwater bodies. Nowadays, the groundwater resources in extended areas with fresh groundwater are threatened, for instance in the south-eastern part of the Netherlands. In this region about $20 \cdot 10^6$ m^3 y^{-1} of groundwater is extracted. In some well fields the nitrate concentration has increased from about 15 mg l^{-1} in 1955 up to 40 mg l^{-1} in the late 1980’s and is still rising since then.

In the last 20 years the NO_3^- concentration of the major spring of the Noor brook, i.e. the Sint Brigida spring, has nearly doubled from about 40 to 70-80 mg l^{-1}. The increase is the response to leaching of nitrates from agricultural areas. Under grassland the increase was from about 20 to more than 100 mg l^{-1} NO_3^- in the last fifty years.

A regional water treatment plant has been built to remove nitrate from groundwater before it is distributed as drinking water. Increasing nitrate concentrations also have negative effects on wetlands, causing botanical composition changes and decreasing the ecological value. Policy makers on nature, environment and drinking water resources want to know whether reduction policy measures undertaken will result in lower nitrate concentrations in the ground- and surface water systems.

Over the last few years several environmental laws and measures have been imposed on the farmers in order to reduce nitrogen application and losses in the Netherlands. Water flow and nitrate concentrations in ground- and surface water have been monitored in the Noor basin since the early nineties. The main spring (Sint Brigida spring) shows a clear upward trend of the nitrate concentration, which has resulted in nitrate concentrations above the drinking water standard (Van Lanen & Dijksma, 1999).

In about 1% of the area, shallow phreatic water levels occur (< 2 m below surface). Deep groundwater tables (up to 45 m deep) prevail. These deep groundwater tables, combined with the poor permeable formations, result in long travel times for water and solute particles. The response of the basin on changing input of nutrients is therefore expected to be slow.

2. MODELLING WATER FLOW AND NITRATE TRANSPORT

The Noor basin (1056 ha) is located in the south-east of the Netherlands and north-east of Belgium. The elevation varies between 240 m a.m.s.l. in the south-east and 91 m a.m.s.l. at the outlet. The Noor brook starts as the Sint Brigida spring at 138 m a.m.s.l., has a length of 3 km and discharges into the Voer in Belgium, which is a small tributary of the river Meuse.

Consolidated Upper Carboniferous shales and sandstone form the impermeable base at a depth of 50-150 m below surface. In the downstream part in Belgium these Upper Carboniferous formations have been eroded and permeable Lower Carboniferous limestones occur, which implies that the impermeable base is at more than 800 m depth. The consolidated rocks are discordantly overlain by subhorizontal Upper Cretaceous deposits, consisting of a sedimentary series of clayey silts interbedded with thin layers of consolidated and fractured sand-stone (Vaals Formation) and soft and poorly bedded chalk (Gulpen Formation). On top of the chalk a poorly-sorted regolith occurs (Eindhoven Formation).

The flow and solute transport model FLONET/TRANS (Guiger *et al*., 1997), was used to calculate past, present and future nitrate concentrations. The model simulates steady state groundwater flow and transient solute transport. Groundwater recharge has been calculated separately for every type of land use and soil for the period 1960-1995. The historical nitrate input has been calculated for different land use types for the period 1950-1995 (Schot *et al*., 1996). FLONET/TRANS does not account for nitrate transport in the thick unsaturated zone. The travel time of NO_3^- in this zone is estimated to be 5-10 years (Juhász-Holterman *et al*., 1989).

The simulated streamlines start at the water table under the plateau and foothill and finally end in the wet valley (Figure 1). Simulated travel times in the saturated zone are maximally 30 and 50 years in the north and south, respectively, for water particles following the longest streamline.

Breakthrough curves for the selected locations within the model domain have been calculated in order to illustrate historical development of the nitrate plume over the last 50 years (Figure 2). A clear upward trend is simulated, which is in line with the observations.

Sensitivity of the nitrate transport has been tested under different groundwater conditions: dry, average and wet years. The model analyses show that the nitrate migration is about twice as fast under wet conditions than under dry conditions. In reality the recharge varies from year to year.

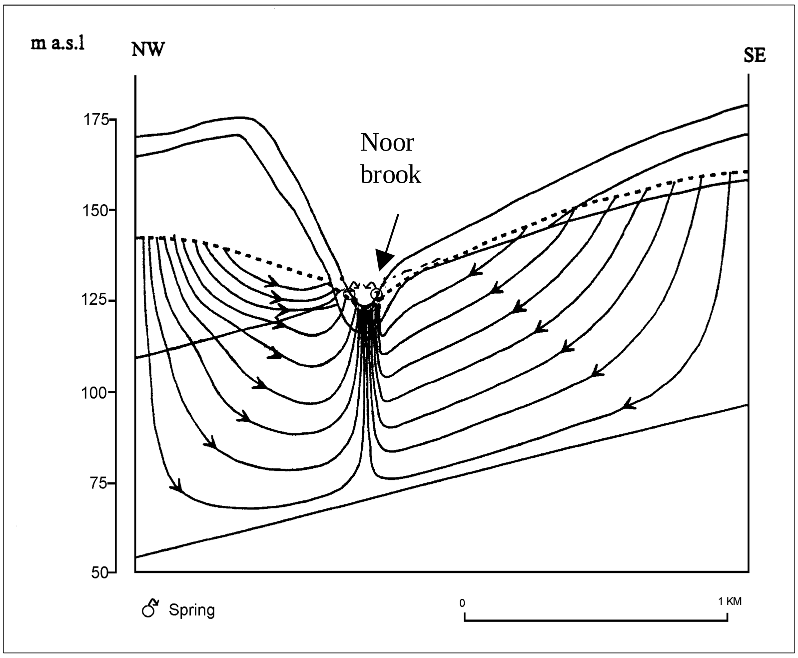

Figure 1: Cross section showing simulated groundwater flow (Van Lanen & Dijksma, 1999).

The model for the prediction of the future nitrate concentrations has been developed upon the basis of data from the 1950-1997 period. The simulation of future trends starts in 1998 and terminates in 2098. The model presumes neither change in flow and transport parameters, nor in groundwater conditions. The average conditions have been assumed to give a good basis for the simulation of the NO_3^- distribution (Kłonowski *et al*., 2000).

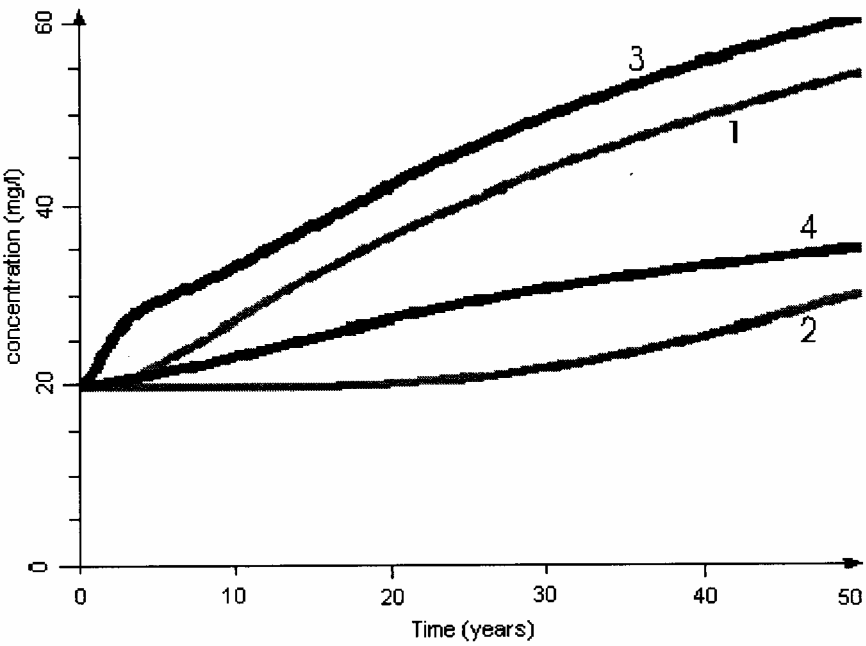

Figure 2: Simulated historical breakthrough curves for average groundwater recharge conditions at different locations in the aquifer (Kłonowski et al., 2000).

Three simulations have been carried out in order to study future developments of nitrate migration in the northern part of the basin. The three scenarios compared to the 1950-

1997 period model, reflect reduction of the NO_3^- input concentration at the phreatic water table by 25, 50 and 75%, respectively.

Reduction of nitrate input by 25% does not cause any decline of the calculated nitrate concentration (Figure 3). The breakthrough curves for the northern plateau (location 1) and northern transition area (3) are very similar and show a gradual increase. For the whole simulation period they exceed the drinking water standard of 50 mg l^{-1} and reach concentrations of above 65 mg l^{-1}, after a century.

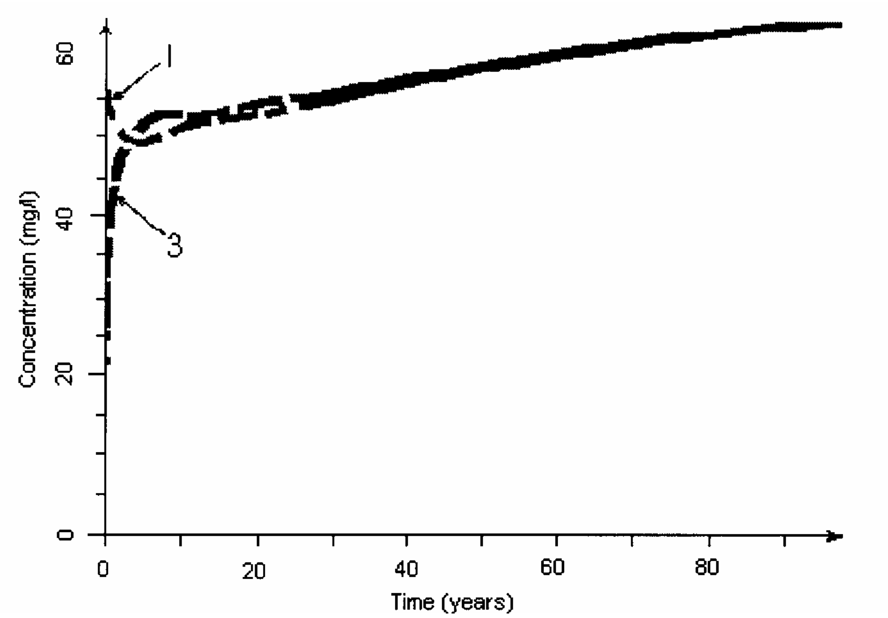

Figure 3: Simulated breakthrough curves for average groundwater recharge conditions at two locations in the aquifer for the 25% reduction scenario (locations: see figure 2).

Reduction of nitrate input by 50% creates stabilization of the present calculated nitrate concentration in the northern part of the basin. The nitrate concentrations for the plateau and foothill are almost constant. Nevertheless, a very slight upward trend still can be recognized. The final concentration for both locations is about 50 mg l^{-1}.

Reduction of nitrate input by 75% causes a decrease of the calculated nitrate concentrations north of the brook in the next hundred years. The final NO_3^- concentration for both locations 1 and 3 is about 30 mg l^{-1} after a century.

3. CONCLUSIONS AND DISCUSSION

The groundwater recharge predominantly follows a long flow path through the chalk and underlying silts and sandstone layers with estimated travel times of up to 50 years. Only in the vicinity of the wet valley do short flow paths prevail, with travel times of a few years.

The simulation of future trends of nitrate concentrations in the northern part of the basin, as a response to nitrogen reduction measures in agriculture, shows that a reduction of the nitrate rich leachate by 25% still results in an increase of the nitrate concentrations in groundwater and surface water in the next century. In the 50% reduction scenario the current nitrate concentrations level stabilizes, but no serious decline occurs in the northern part of the Noor basin. A dramatic decrease of the nitrate input, i.e. the 75% reduction scenario, results in slowly decreasing NO_3^- concentrations to a value of about 30 mg l^{-1} (mean NO_3^-

input). This value will be reached after decades because of the long travel times in the Cretaceous multi-aquifer system with deep water levels. The monitoring and modelling work in the Noor basin points out that even if agricultural practices change substantially, the groundwater resources and nature reserves in the Belgian-Dutch chalk unit will suffer from excessive nitrate concentrations for many years. Nature management authorities have to realize that a restoration of the botanical composition associated with groundwater rich in $CaCO_3$ and poor in nutrients, is not to be expected within the first decades. Irreversible processes might already have taken place.

ACKNOWLEDGEMENT

The research was carried out as part of the program of the Wageningen Institute for Environment and Climate Research (WIMEK/SENSE).

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Influence of drained lands on water quantity and quality in foothill agricultural basins of Bohemia

Dolezal, F., Z. Kulhavy, T. Kvitek, J. Peterkova, M. Soukup & M. Tippl

Research Institute for Soil and Water Conservation
Zabovreska 250, 156 27 Praha 5 - Zbraslav, Czech Republic
Email: dolezal@vumop.tel.cz

ABSTRACT

The paper presents selected illustrative results from three small experimental basins situated in foothill zones of various Bohemian highlands, mainly with agricultural land use. The tile-drained fields occupy about 15 to 40 % of the total area of the basins. Drainage runoff from differently located drainage systems can be characterized by its probability-of-exceedance curve and by the proportion of quick runoff. During flood events of small to medium size, the drainage runoff from ploughed lands contributes significantly to the flood volume. The runoff from tile drainage typically reveals high concentration of nitrate as long as the overlying fields or the lands in the recharge zone of the drained aquifer are ploughed. The reduction of nutrient load received from the topsoil leachate can be achieved by a combination of the reduction of ploughed land areas with the improvement of fertilizer application practices and the retardation of runoff from drainage systems.

1. INTRODUCTION

Drainage of overwetted agricultural lands became an essential component of agronomy in humid, subhumid and transitional climates. Recently, however, the drainage has also been recognized as a factor which, allegedly, exacerbates harmful effects of floods, deprives the landscape of moisture and accelerates the leaching of nutrients and pollutants from the soil. A specific feature of drainage systems in countries of Central and Eastern Europe (such as the Czech Republic) is that most of them were large scale schemes under the massive support of the state. As a result, some potentially valuable wetland sites were drained and destroyed, while drainage was also frequently carried out on areas that had not been waterlogged. The result in the Czech Republic is an intensively drained agricultural landscape, where about 30 % of the total arable land area has been tile-drained.

A recent phenomenon with great hydrological significance has been a decline in the intensity of agriculture in Central and Eastern Europe over the last decade. Fertilizer application rates and numbers of domestic animals fell drastically and some lands (including some drained areas) have been set aside or converted from arable land into grassland or forest. There is a general perception that there is a lack of reliable criteria to allow assessment of whether or not a site is economically and environmentally suitable for such a conversion. The combination of hyper-intensive land drainage with the far-reaching land use changes leads to hydrological and environmental consequences that are difficult to predict and quantify. The hydrological role of drainage systems in interaction with land use changes and other factors is significant and therefore deserves to be studied quantitatively.

2. CHARACTERISTICS OF EXPERIMENTAL BASINS

The paper reports results from three experimental basins, situated in foothill zones of various Bohemian highlands. Table 1 presents an overview of basic basin characteristics. All basins are small (few km^2). Their land use is prevailingly agricultural (mainly arable land, intermingled with segments of grassland and forest). Forest, however, prevails in the Cerhovicky potok basin. In this basin, much of the arable land has recently been set aside, and can be therefore regarded as grassland. In the past, this particular experimental basin had reached farther downstream and comprised a larger proportion of arable lands. However, this downstream part was lost for further research because of highway construction between 1994 and 1995. The texture of the soils in all basins varies between loamy sand and clayey loam, being distinctly heavier in the Cerhovicky potok basin. The soils are mainly underlain by acid crystalline (igneous or metamorphic) rocks with low permeability. The tile-drained fields occupy about 15 to 40 % of the total area of the basins.

Table 1: Basic characteristics of experimental basins.

Name of basin	Cerhovicky potok	Cernici	Kopaninsky tok
Average latitude	49° 51' N	49° 37' N	49° 28' N
Average longitude	13° 50' E	15° 04' E	15° 17' E
Altitude [m]	390 - 572	460 - 561	467 - 578
Area [km^2]	7.31	1.42	6.64
% arable land	18	65	52
% grassland	22 [1]	14	14
% forest	61	19	30
Average annual precipitation [mm] [2]	617 (Holoubkov, 1901-1950)	722 (Cechtice, 1961-1995 [3])	665 (Humpolec, 1901-1950)
Average annual air temperature [°C] [2]	7.5 (Jince, 1901-1950)	7.5 (Cechtice, 1961-1995 [3])	7.0 (Humpolec, 1901-1950)
Parent rock	schist	paragneiss	paragneiss

[1] *Including the set-aside land.*

[2] *According to weather station and period indicated.*

[3] *The years 1968, 1971, 1986-1990 are missing.*

3. WATER QUANTITY

The drainage runoff and its contribution to the total runoff in small streams has been studied both by deterministic and stochastic means. The probability-of-exceedance curves of instantaneous or average daily tile-drainage runoff typically consist of three parts (Dolezal *et al*., 2000, 2001). The shape of the first part at low or zero discharges depends on whether or not the drains are in contact with a permanent aquifer. The second part comprises the cases when the soil profile itself is being drained, while in the third part the discharges are limited from above by the hydraulic capacity of the drainage system. In the range of medium discharges, the recession limbs of drainage hydrographs can be analyzed and interpreted in terms of soil properties and drainage system geometry (Dolezal *et al*., 2000). Figure 1 shows typical examples of the probability-of-exceedance curves for small drainage systems. The system S1 (0.605 ha) is located in the valley and collects quick runoff flow from surrounding slopes and from the valley itself, while S2 (1.815 ha) drains a wetland (the discharge zone of an aquifer) lying uphill.

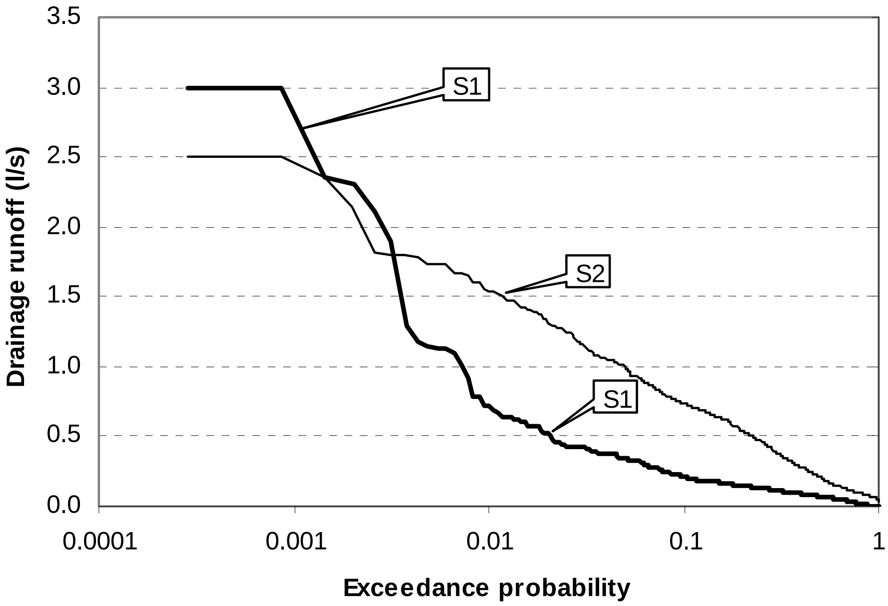

Figure 1: Probability-of-exceedance curve of average daily drainage runoff from two differently located drainage systems. Cernici basin, 1994-1999.

Another way of analyzing drainage runoff is to apply a separation procedure that is normally used for separating the direct runoff from baseflow in a stream hydrograph (Kulhavy *et al*., 2001). In the case of drainage runoff, we can separate in this way the quick runoff (the water that found its shortest way from the ground surface into the drain) from the baseflow (the water that passed through a groundwater aquifer before it emerged as drainage runoff). The drainage systems that drain discharge zones of aquifers generally have a higher proportion of baseflow in their hydrographs. This is documented in Figure 2, which relates to the same drainage systems as Figure 1. The drainage system S1, which lies in the valley, exhibits a significantly higher proportion of quick runoff, because it is fed by the surface water and the rapidly flowing perched groundwater in the top layer of the alluvial soil and of the soils on the adjacent slopes.

Finally, by comparing drainage runoff with the adjacent stream runoff, we can estimate to what degree the drainage runoff contributes to the stream runoff over periods of high discharges. Figure 3 compares average daily specific runoff rates from two different parts of the Cerhovicky potok basin. B1 (315 ha) is the upper part of the basin, mostly forested but containing also meadow areas intermingled with small patches of ploughed land. S7 (40.5 ha) is a large drainage system under ploughed land. Figure 3 demonstrates that, in many cases, the runoff events in B1 do not occur at the same time as analogous events in S7, because of different runoff formation mechanisms, i.e., different time constants, and also because of the spatial heterogeneity of precipitation. In the remaining cases, when the events occurred more or less simultaneously, the points in the graph group along a straight line. The slope of this line suggests that the specific surface runoff from forest and meadow is about five times smaller than the specific drainage runoff from ploughed lands. However, one must realize that drainage systems usually collect water from an area much larger than the area they physically occupy.

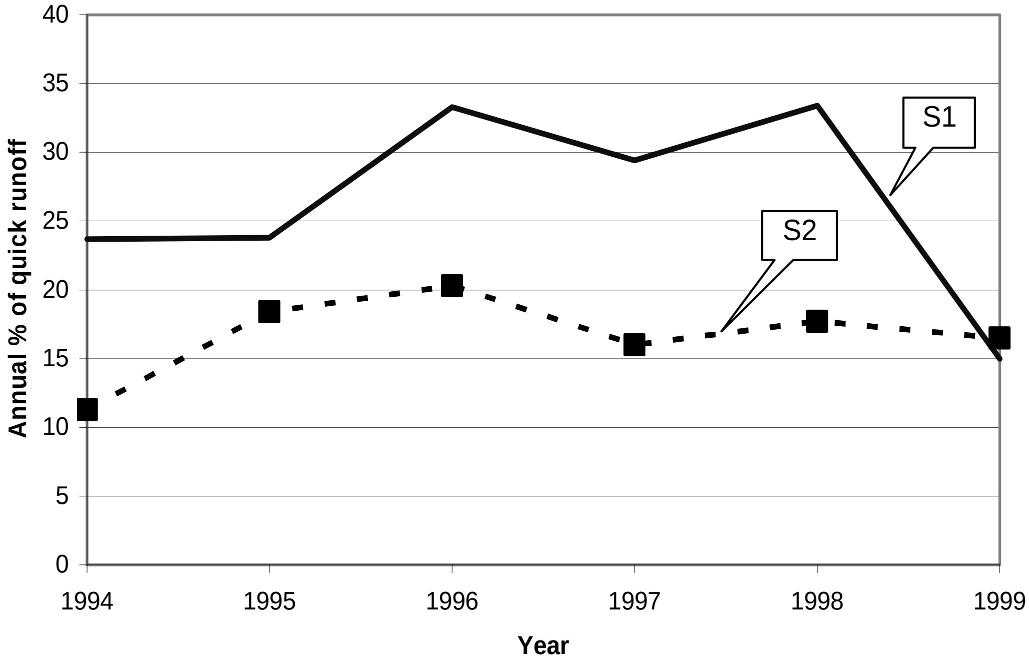

Figure 2: Results of a hydrograph separation procedure applied to drainage runoff. Cernici basin 1994-1999.

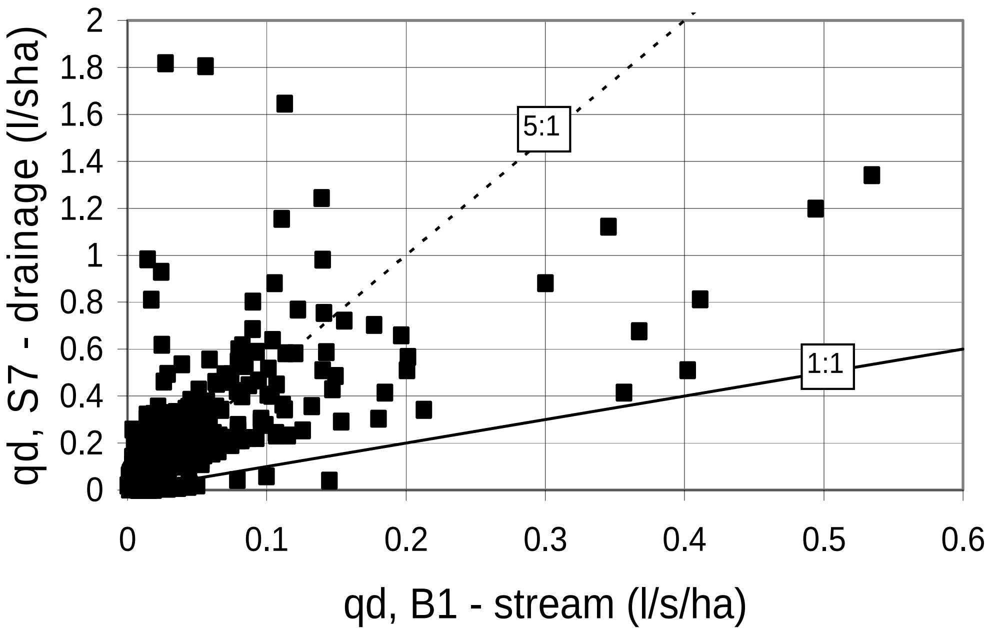

Figure 3: Comparison of average daily specific runoff values from two different parts of the Cerhovicky potok basin, 23/10/1996-31/8/1999.

4. WATER QUALITY

The results of water quality measurements show that the runoff from tile drainage typically reveals high concentration of nitrate, as long as the overlying fields or the lands in the recharge zone of the drained aquifer are ploughed. Management of ploughed lands inevitably means that they are left without vegetation over a certain part of the year (in autumn, winter and/or spring). At these times, the inorganic soil nitrogen, supplied by mineralization of organic matter, is easily leached out from the topsoil rather than taken up by the plants.

Water in surface streams of agricultural basins also contains relatively high amounts of nitrate. Some results (Kvitek, 1994, 1999) indicate that this is caused by a high proportion of ploughed land in the basins rather than by a high proportion of drained lands. In other words, the perched groundwater over the weathered crystalline bedrock receives the nitrate quickly from the topsoil and transmits the load into the stream baseflow. There is not much opportunity for denitrification and the transfer is completed with an efficiency and speed not much lower than the tile-drainage runoff. The concentrations of other soluble forms of nutrients (NO_2^-, NH_4^+, PO_4^{3+}) in drain water as well as in stream water is also significant. Water emerging as springs often appears, in the basins studied, in the upper or middle parts of slopes. Its underground circulation through weathered and fissured zones of the crystalline bedrock is also short, but its time of residence is longer than that of the drainage water or of the perched groundwater. If its recharge zones, which of course are difficult to delineate, lie under forest and grassland, then the concentrations of nitrate in spring water are lower than those found in drain water, perched groundwater and stream water (see Table 2). Table 2 also refers to the Czech standard CSN 75 7221 (1998) water quality classes (III – polluted, IV – highly polluted, V – very highly polluted). The decline of fertilizer application rates in the nineties resulted in reduced but still relatively high concentrations of pollutants in drainage water. This reduction occurred with about a 5-year delay after the decrease of fertilizer application rates. Unfortunately, over the last few years the concentrations tend to rise again.

Table 2: NO_3^- concentration (mg l^{-1}) in drainage runoff and in springs, Kopaninský tok.

Runoff from	**Tile drainage outlets**				**Springs**		
Sampling site	**P4.1**	**P6**	**P7**	**P8**	**T1**	**P1**	**P5.1**
Land use	arable				arable/forest	grass/forest	forest
Maximum	142	77	43	47	37	22	25
Minimum	3	17	9	12	8	3	6
Average	60	50	26	28	24	17	11
95 % quantile	94	74	38	43	36	21	19
Quality class (CSN 757221, 1998)	V	V	IV	IV	IV	III	III

5. CONCLUSIONS

Strictly speaking, the results discussed above are only valid for small agricultural basins in the foothill zone of Bohemian highlands. Extrapolations to other conditions should be made with caution. It appears that the contribution of drainage to flood runoff may be significant but varies considerably, depending on local conditions (soil permeability, size and other parameters of the drainage system, hydrogeology, etc.) and the nature of the flood generating event (Fidler & Soukup, 1998). The maximum specific drainage runoff rates after extreme rain or snowmelt events seldom (once over several years) exceed 3 l s^{-1} ha^{-1}. Cases when a drainage system drains a discharge zone of an aquifer can be harmful for the landscape because the water that has been drained away cannot be used by vegetation on the spot. The available results also lead to a conclusion that the desirable goal, i.e., the reduction of nutrient load from the topsoil leachate received by streams, drinking water reservoirs and, finally, seas, can be (and is being) achieved by reduction of ploughed land areas in mountainous and foothill regions, i.e., conversion of ploughed land into grassland and forest. These measures should be accompanied by systematic implementation of sound practices of fertilizer application (as envisaged by the EU Nitrates Directive, cf. Anonymous, 1991). It is also advised that the runoff from drainage systems be retarded by simple structures in order to reduce the peak flow rates as well as the total runoff volumes and to extend the residence times (Soukup & Kulhavy, 2000). The research into quantification of these aspects continues.

ACKNOWLEDGEMENT

The research was partly financed by the National Agency for Agricultural Research as projects no. NAZV RE 5501, EP 096006150 and several other projects, by the Grant Agency of the Czech Republic as projects no. 502/95/0826 and 103/99/1470, and by the Ministry of Agriculture and Ministry of Environment of the Czech Republic.

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Groundwater runoff in a small mountainous basin: testing a separation method based on groundwater table and discharge measurements

Holko, L.[1], A. Herrmann[2], M. Schöniger[2] & S. Schumann[2]

[1] Institute of Hydrology, Slovak Academy of Sciences
Ondrasovecka 16, 031 05 Liptovsky Mikulas, Slovakia
Email: holko@svslm.sk
[2] Institute of Geography and Geoecology, Technical University Braunschweig
Langer Kamp 19c, D-38106 Braunschweig, Germany

ABSTRACT

Using the small mountainous and forested research basin of Lange Bramke in the Harz Mountains, Germany as an example, it is shown that different runoff separation methods produce several convergent results. The starting point is the envelope line method for groundwater table-discharge relationships. This is found to yield reliable results compared to those from another graphical hydrograph separation technique, with three subsurface components and based on a linear storage concept. The results suggest in each case that pre-event is groundwater, since lateral flow is negligible. This is confirmed by the environmental isotope tracer technique. The convergence of results for individual runoff components is remarkable; however their different origins and validity range should not be forgotten. The main result is that the envelope line method is a simple and reliable way of computing daily groundwater runoff.

1. INTRODUCTION

Hydrograph separation using stable environmental isotopes has been carried out in a number of geographically different study basins, all of which have provided similar results. Accordingly, “pre-event water” is a dominant component of total basin runoff (Herrmann, 1997). Although pre-event water is not a genetic category, it is often, though not correctly, understood as groundwater runoff. The application of isotopic runoff separation techniques needs above all careful sampling and analysis in well-equipped laboratories. Hence, in most cases, the method cannot be used on a long-term basis. In this context, it has been noticed by Holko (1995) that the results of isotopic runoff separation are quite similar to those provided by a separation method proposed by Kliner & Knezek (1974), which is based on groundwater table-discharge relationships and runs on daily basis.

The objective of this study is to compare the results of the Kliner-Knezek separation method with those obtained from other hydrograph separation techniques for the same basin. These include DIFGA (Schwarze, 1985), which uses a linear storage concept, or the analytical environmental isotope technique (e.g. Buttle, 1994; Herrmann, 1997; Kendall & McDonnell, 1998). This can easily be done, because the isotope technique (Herrmann *et al.,*

1989) and DIFGA (Schwarze *et al.,* 1994) have already been applied to Lange Bramke research basin with success. A comparison of findings should finally establish whether the environmental tracer technique can be replaced by less costly methods that using only routine data.

2. METHODS AND EXPERIMENTS

2.1. Groundwater runoff separation

There are two ways to approach the study of drainage basin groundwater reserves. Synthetic or graphical techniques for separating the groundwater runoff component call for long-term hydrological data series of required variables of at least one year, and preferably ten years length. In general, daily routine field data are sufficient. Analytical approaches based on the use of environmental tracers like isotopes or major ions also enable treatment of single precipitation–runoff events, but their data requirement is much more demanding. These techniques are characterized briefly below with respect to the main topic.

2.2. Synthetic approaches

Envelope line (Kliner & Knezek, 1974)

In the normal case of hydraulic connection between aquifer and river course, a close relationship should exist between groundwater and stream water levels. Groundwater runoff can be determined by plotting discharge against groundwater table level. Usually the top boundary of the concentration of dots in the diagram describes an envelope line that represents the flux formed by groundwater runoff (Figure 1). This line can be used to estimate groundwater runoff for a measured groundwater table.

If the groundwater table and discharge data span a period of several years, the envelope lines can be constructed separately for individual years, or a single master envelope line can be used for the data set.

The envelope line separation method has been applied to a data set from hydrological years 1987-1999.

DIFGA (Schwarze, 1985)

The computer-aided hydrograph differences method (DIFGA) is a tool developed to assess runoff components and residence time regimes by assuming that runoff formation and concentration processes can be described by the parallel connection of single linear storages. DIFGA allows determination of four runoff components: quick (RD1) and delayed direct runoff (RD2), with the latter following preferential flow paths in the present study basin through macro-pores and fractures; quick (RG1) and delayed baseflow (RG2), with the latter describing the base reserve of the basin and different mean transit times with the appertaining storage constants and reservoirs. DIFGA was formerly applied to a 40 years data set (1948-1987) of the study basin (Schwarze *et al*., 1991).Those results were compared to other central European highland basins, including Saxonian Ore Mountain and Slovak limestone and dolomite basins in the Váh region (Schwarze *et al*., 1994). DIFGA also proved to be a useful tool for regionalising runoff components.

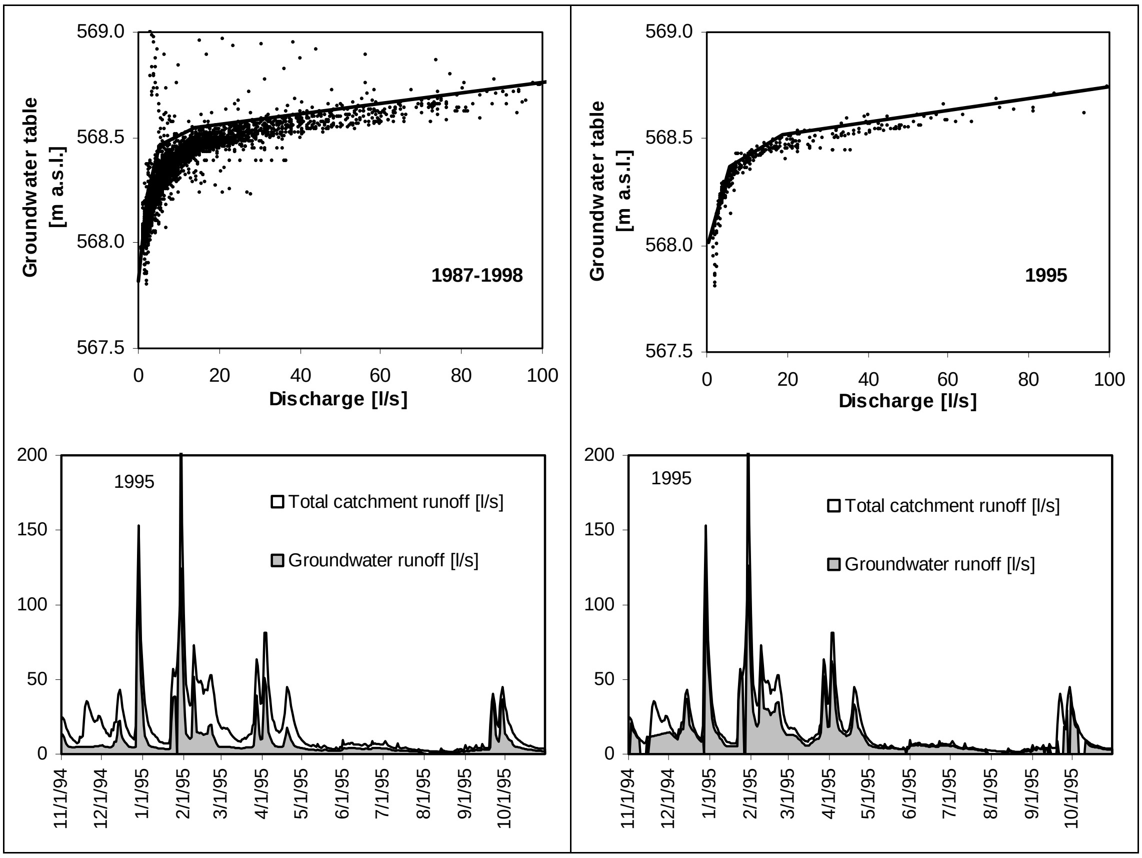

Figure 1: Envelope line and groundwater runoff in hydrological year 1995 as derived from Kliner & Knezek (1974) method; left side of shows the master envelope line determined for all the data (1987-1999), right side shows the envelope line determined only for data from the year of 1995.

2.3. Analytical approach by the environmental isotope tracer technique (see e.g. Kendall & McDonnell, 1998)

Environmental isotopes like tritium, deuterium and oxygen-18 allow separation of event from pre-event water, with the latter representing subsurface water in general originating from the groundwater reservoir. The lateral water flux from the unsaturated soil zone towards the river course can be neglected. This is the case in the Lange Bramke study basin (Herrmann *et al*., 1989). The respective flux is usually called interflow. In this context, ample discussion of soil water influence on separation results, although not relevant in our case, can be found in Kendall & McDonnell (1998), and of the interpretation of separated runoff components with respect to traditional concepts also in Buttle (1994).

In a second step, the isotopes may allow calculation of the mean transit times of water (t_o) for the system under investigation by solving the inverse problem. This consists of applying appropriate exponential or dispersive basin response (transfer) functions to isotopic input and output concentrations. Complication arises in double-porous storage systems, like the fractured rock aquifer in our case, where tracer diffusion in micro-pores is also a relevant physical process besides dispersion in fractures. As a consequence, the resulting mean transit time of tracer (t_t) is higher. However, t_o, the hydraulic target parameter, can be found by introducing the retardation factor (R_p) for the isotope used, which itself can be determined from weighted mean area micro- and macro-porosities.

Relevant hydrological findings using isotope techniques, and referring to the 1980-1989 study period, are compiled in Herrmann *et al*. (1989). They have been discussed together with those from DIFGA in Schwarze *et al*. (1991).

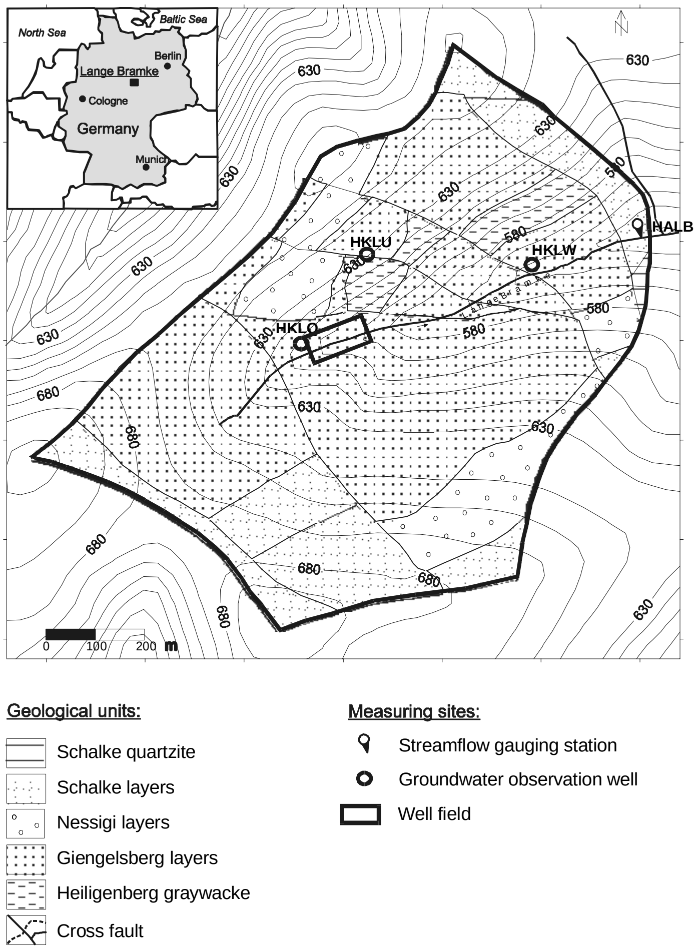

Figure 2: Topographic map of Lange Bramke research basin with geology and relevant instrumentation.

2.4. Lange Bramke study basin

The Lange Bramke hydrological research basin situated in the Harz Mountains, Lower Saxony, Germany (Figure 2) has been studied since 1948. It covers 0.76 km^2, it lies between 543-700 m a.m.s.l., and it is 90% covered by Norway spruce forest. The basin has three distinct hydrological storages:

- The upper unsaturated soil zone of mean 3.5 m thickness, composed of residual weathering material, allochtonous Pleistocene solifluidal materials, lying over fissured and faulted bedrock;
- The underlying semi-confined fissured rock aquifer consisting of heavily folded and fractured Lower Devonian sandstones, quartzites and slates which are weathered and partially unsaturated on top;
- The porous aquifer filling the valley in the centre of the basin.

Major equipment includes several groundwater observation wells that were installed in the second half of the eighties. In this study, the groundwater table levels measured with an

Ott recorder in the well HKLQ were used. This 15 m deep well, which has a filtering section at 13-15 m below ground surface, is located almost in the centre of the basin on the left hand toe-slope.

3. RESULTS

3.1. Findings from the envelope method (Kliner & Knezek, 1974)

Determination of the envelope line is largely subjective. In most years, the distribution of data defines rather clearly where the lines should be drawn. However, in some years, quite a few points are found outside the area determined by the line. The separated contribution of groundwater runoff to total basin runoff was rather high (Figure 3). The mean groundwater contribution according to master envelope line was 54%. As many as 61% of all the results fell into the interval of 40-70% and the standard deviation was 17%. When we used specific envelope lines for particular years, the mean groundwater contribution was 77%, but the histogram shows that higher groundwater contributions are much more frequent - 68% of results lie within interval 70-100% with a standard deviation of 15%.

Separations showed that groundwater runoff also contributed actively to basin runoff during single flood events and periods (Figure 1).

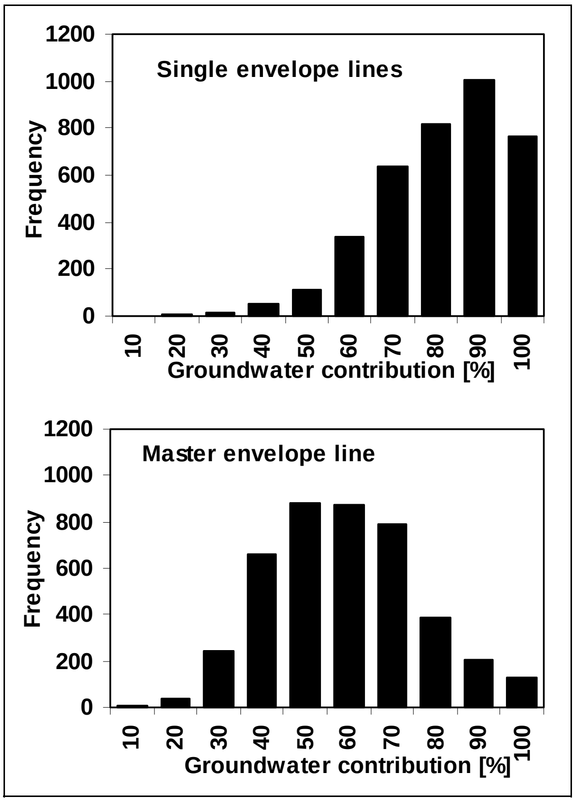

Figure 3: Histograms of groundwater contributions calculated according the master envelope line and specific envelope lines determined for particular years.

3.2. Findings from environmental isotopes and DIFGA

Taking different study periods within the >50 years long hydrological observation series for Lange Bramke, the order of magnitude of groundwater discharge is reconfirmed by the isotope hydrological findings. The value t_o of this component is about 1.5 yr, and when passage through the upper unsaturated soil zone is neglected t_o reduces to approximately one year. The annual recharge rate of the dynamic groundwater component amounts to 620 mm. Accordingly, the volume of mobile water (V_m) in this storage corresponds to approximately 1000 mm. One-sixth of the groundwater volume is stored in the valley filling, which has an effective porosity (n_{eff}) of 32%, and the rest in the fissured rock aquifer (t_o=1.2 yr. with R_p=1.45; fissure porosity n_{eff} =1.1%; matrix porosity n_p=0.5%). Considerable amounts of water are found in the 3.5 m thick near-surface unsaturated soil zone where the total porosity (n) is 20%, corresponding to little more than 1/3 of the whole subsurface water reserves.

Only 12% of the discharge is event water, which explains the high annual groundwater recharge rate for Lange Bramke of 620 mm. This compares to the 378 mm per annum (master envelope line) or 539 mm per annum (envelope lines for single years) from more traditional methods like Kliner & Knezek (1974), or to the estimates of 220-290 mm obtained form methods using low flow indices or hydrographs as a basis (Herrmann *et al.*, 1989). The runoff formation mechanism that explains the considerable groundwater exfiltration during events is discussed for instance in Herrmann (1997). From recent artificial tracer experiments, it can be concluded that the turbulent high-speed groundwater flow of up to >10 m h^{-1} passing through the major cross-faults of Lange Bramke (Maloszewski *et al.,* 1999) contributes significantly to flood hydrographs.

In principle, DIFGA confirms the isotope hydrological findings. The surface component (RD1) is similar at 12%. The three subsurface runoff components, i.e. the sum of macro-pore plus fracture runoff (RD2), and of the two slowest initial (RG1) and delayed baseflow components (RG2), are comparable with those obtained from isotopic studies, but lower than those from envelope line separations. The mean transit time of total runoff as calculated from the weighted means of the single runoff components is 3.1 yr which is exactly the mean transit time of tracer (t_t) found from the isotope technique.

A new finding is the fact that the fractured rock aquifer can be further discriminated according to storage volume (V) and residence time (t). Contributing runoff flux components and relative storage volumes are: RD2=222 mm yr^{-1} and VD2=2%; RG1=250 mm yr^{-1} and VG1 9%; RG2=133 mm and VG2=89%. Accordingly, the respective mean residence times come to 0.063 yr, 0.272 yr and 7.260 yr, with the weighted average being $t=t_t$=1.7 yr.

4. DISCUSSION AND CONCLUSION

Discussing runoff components frequently causes misunderstanding if their definitions and origins are neglected. This can easily be demonstrated with existing runoff formation concepts. As we learnt from the isotopic hydrological findings, the traditional runoff formation concepts should be revised to be relevant for ecohydrological purposes. The same problem exists for this study, i.e. each individual approach defines a specific but different combination of groundwater reserves. Care needs to be taken, therefore, when comparing results from different source without considering their limit of validity. For instance, direct runoff in the sense of isotopically defined event water does not have the same origin as an apparently similar component which has been graphically separated from a hydrograph. Consequently, although we are talking here about convergent results, there cannot be exact agreement because of the different methodical approaches to the problem. The message here is that there are a number of such convergences, which means that a number of separation methods exists, the choice of which depends on the purpose and aims of the study and data availability.

In this sense it seems that the groundwater runoff separation technique proposed by Kliner & Knezek (1974) is a simple way to compute daily groundwater discharge. The respective separation results seem to be realistic in relation to the results drawn from the environmental tracer approach, although the latter gives additional information about the age of this component. Furthermore, the DIFGA technique proves that the groundwater reserve of the basin is made up by at least two components, which originate from different hydraulic systems, and supports need for a multilateral integrated scientific basin approach.

The main result is that the most expensive isotope technique needs only to be used for calibrating the more suitable, and also more reliable, empirical approaches to groundwater systems analysis in small basins.

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Snowmelt runoff in two mountain catchments

Kostka, Z.[1], L. Holko[1] & A. Kulasova[2]

[1] *Institute of Hydrology, Slovak Academy of Sciences*
Ondrasovecka 16, 031 05 Liptovsky Mikulas, Slovakia
Email: kostka@svslm.sk
[2] *Czech Hydrometeorological Institute*
Na Sabatce 17, 143 06 Prague 4, Czech Republic

ABSTRACT

Hydrological modelling of snow accumulation, melt and catchment runoff in two small mountain catchments (Jalovecky Creek, Slovakia and Uhlirska, Czech Republic) was supplemented by isotopic separations of hydrographs. Modelling of the catchment mean snow water equivalents was successful. Isotopic separations proved that there are significant contributions of old water to melt water events. Comparison of measured runoff, modelled outflows from the snow cover and new water contributions derived from isotopic separation indicated the important role of the peaty soils in the Uhlirska catchment in runoff generation.

1. INTRODUCTION

Mountain catchments present a permanent challenge for hydrological research and modelling because of their complex natural conditions, a general lack of data and, at the same time, the fact that they have an important impact on the hydrological cycle and water supply in large parts of the continents. The aim of this study was to use a combined application of mathematical modelling and isotopic runoff separation to study runoff generation in two small mountain catchments during the snowmelt season of 1999.

Table 1: Basic characteristics of the Jalovecky Creek and Uhlirska catchments

Parameter	**Jalovecky Creek**	**Uhlirska**
Area [km^2]	22.2	1.87
Elevation [m.a.s.l.]	800-2178	775-886
Mean slope [°]	30	3.5
Bedrock	granodiorite, schist	granite
Vegetation	coniferous forest 44%, dwarf pine 32%, meadows and bare rocks 24%	coniferous forest 49%, meadows 51%
Precipitation [mm]	1435	1400
Runoff [mm]	858	1018
Air temperature [°C]	3.5	5.1

2. RESEARCH CATCHMENTS

Data from two snow-affected, small experimental catchments, the Jalovecky Creek catchment (in the Western Tatra Mountains, Slovakia) and the Uhlirska catchment (in the Jizera Mountains, Czech Republic) were used in the study (Figure 1). While both catchments are situated in mountains, the former represents high mountain conditions (steep slopes, large vertical zonality, large percentage of glaciofluvial sediments) and the latter is a typical highland catchment (mild slopes, peaty soils covering much of the catchment). The basic characteristics of both catchments are given in Table 1.

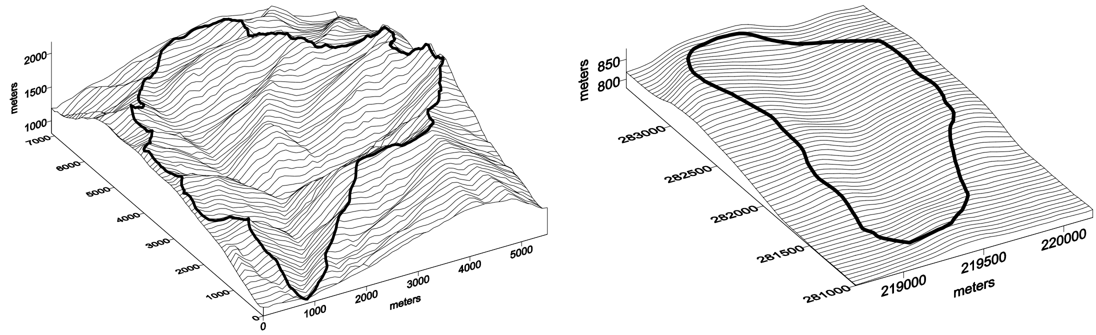

Figure 1: The Jalovecky Creek (left) and the Uhlirska catchments (right).

3. METHODS AND DATA

3.1. Snow accumulation and snowmelt modelling

The distributed WaSiM-ETH model (Schulla, 1997, 1999) was applied to the simulation of snow cover temporal and spatial dynamics in both catchments. WaSiM-ETH model is a distributed hydrological model with modular structure giving the alternative of spatial or temporal resolution of simulations. The minimum meteorological input data requirements are precipitation and air temperature time series, with a daily or shorter time step, from at least one meteorological station. In addition, spatially distributed data sets (grids) are required – including a digital elevation model, aspect, slope angle, topographic index $\ln(a/\tan\beta)$ (a is the area draining through a point per unit of width and β is the local slope, Beven & Kirkby, 1979), land use and soil types.

The altitude dependent regression method combined with an inverse distance weighting routine was used for the interpolation of meteorological input data where two or more stations were available. In the case of input meteorological data being available from only one station, the same values were used for the whole catchment.

The Penman-Monteith approach (Brutsaert, 1982) is used for potential evapotranspiration calculation. The real evaporation is reduced to below the potential evaporation if the content of the soil moisture storage drops below a specified level. A simple bucket approach is used for interception calculation, with a capacity depending on the leaf area index, the vegetation coverage degree, and the maximum height of water at the leaves. The interception is calculated after the snow model, so that the snow melt is flowing into the interception storage as well as rain water.

Modelling of snow accumulation and snowmelt can be performed using a temperature-index-approach, a temperature-wind-index-approach, a combination approach after Anderson (1973) and an extended combination approach after Braun (1985). The latter two approaches were developed for daily time steps.

3.2. Isotopic runoff separations

The stable natural isotope of ^{18}O was used to separate the old (event) and new (pre-event) water contributions during the main phase of snowmelt in spring 1999. Separation is performed according to the well known formula:

$$X_n = 1 - \frac{\delta_t - \delta_n}{\delta_o - \delta_n}$$

where X_n is fraction of the new water in catchment runoff, δ_t, δ_n, and δ_o are concentrations of ^{18}O in the stream at catchment outlet, in melting snow and in the stream at the catchment outlet before the event, respectively.

Old water represents the contribution of water stored in the catchment before the event, in this case caused by snowmelt. New water represents the contribution from melting snow. The isotopic characteristics of the new water in both catchments were estimated from the snow core samples.

The hydrological model WaSiM-ETH also provides results on snowmelt inputs into the catchment. The model was run with a daily time step. Because we wanted to analyse the modelled snowmelt inputs into the catchment in order to compute the new water contributions with an hourly time step, continuous separation of the hydrograph was needed. To achieve this we used the method of averages i.e. the relationship between the isotopic composition of stream water at the catchment outlet and discharge was used to determine the continuous values of isotopic composition of stream water δ_t. Corresponding values of δ_n were determined on the basis of linear interpolation of catchment mean values of $\delta^{18}O$ of the snow cover at the beginning and end of the snowmelt (Holko, 2000).

4. RESULTS

4.1. Snow accumulation and snowmelt modelling

Catchment runoff and snow cover in winter 1998/99 were simulated and calibrated against field measurements. In the Jalovecky Creek catchment, 20 sites with snow water equivalent values were available, and in the Uhlirska catchment there were 7 snow measurement sites (Figure 2). Model simulations in both catchments included: interpolation of the meteorological input data; shadowing and exposure- dependent adjustment for radiation and air temperature; evapotranspiration calculation after Penman-Monteith; snow accumulation and snow melt using the extended combination method; as well as routines for interception, infiltration, surface runoff generation and soil storage calculation including interflow and baseflow.

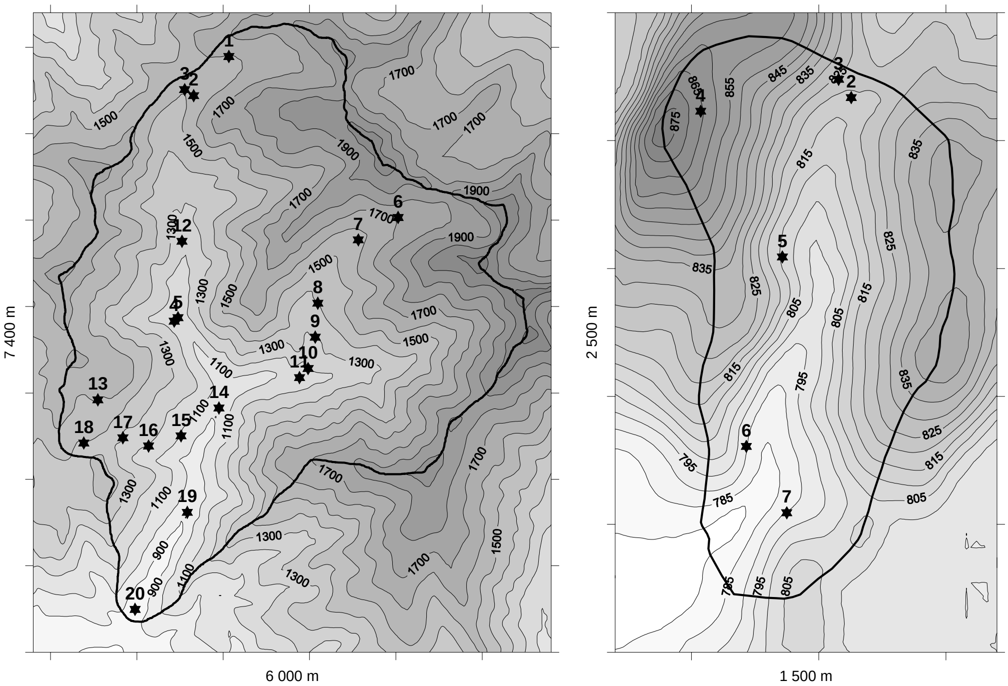

Figure 2: Catchments topography and location of snow measurement sites; left – the Jalovecky Creek catchment, right – the Uhlirska catchment.

The parameter sensitivity analysis was performed in order to find the most sensitive parameters with respect to the modelled discharges and to the partitioning of the precipitation water into water balance components. The values of the snow subroutine parameters that resulted in the best agreement between measured and modelled snow water contents are given in Table 2.

Table 2: Snow subroutine parameters applied at simulations.

Parameter	**Jalovecky Creek**	**Uhlirska catchment**	**Explanation**
T_{trans}	1.0	1.0	half of the temperature-transition range from snow to rain
$T_{R/S}$	0.5	0.2	temperature at which 50 % of precipitation is falling as snow
$T_{0,m}$	0.5	0.2	the threshold temperature for beginning of snow melt
C_1	0.5	0.6	temperature dependent melt factor
C_2	0.3	0.4	wind dependent melt factor
C_{rfr}	0.8	0.9	coefficient for refreezing
C_L	0.2	0.1	maximum capacity of the water storage as fraction on the total storage
RMF	4.5	3.5	radiation melt coefficient

Snow accumulation and melt was modelled using several approaches (temperature-index approach, temperature-wind-index approach, combination approach after Anderson and extended combination approach after Braun). The mean variation of snow water equivalent in the catchment was modelled reasonably well. The best results were obtained by the combination approaches, where total snow melt is composed of radiation melt, melt from sensible heat, melt from latent heat and melt from energy import from precipitation. The snow cover simulation results are shown in Figure 3.

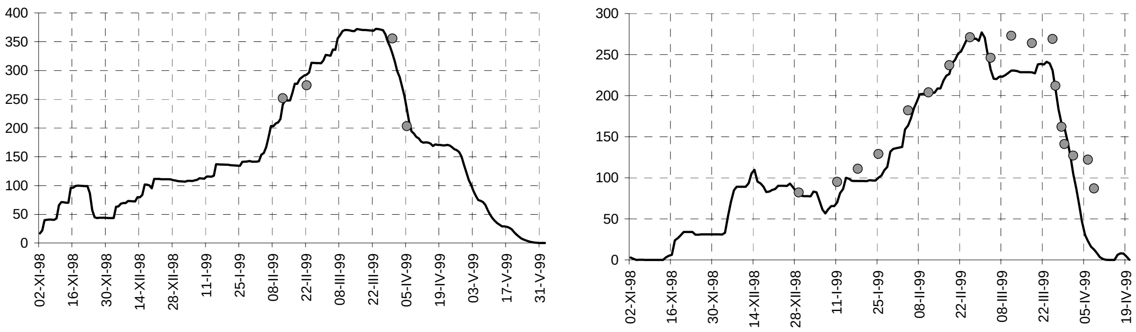

Figure 3: Comparison of the catchment average values of simulated and measured snow water contents [mm] (left – the Jalovecky Creek catchment, right – the Uhlirska catchment).

Runoff modelling indicated that in the Jalovecky Creek catchment (high mountain relief) baseflow represents the dominant part of total runoff during the main snowmelt event. The Uhlirska catchment (highlands hilly relief) has a different type of snowmelt regime. During the winter season studied, several flood events occurred. The baseflow contribution to the total runoff during the main snowmelt event was 75% in the Jalovecky Creek catchment and 28% in Uhlirska catchment. The results of modelling indicate substantially lower baseflow in the Uhlirska catchment compared to the Jalovecky Creek catchment (Figure 4). However, the timing of modelled events in the Jalovecky Creek catchment did not fit the measured runoff.

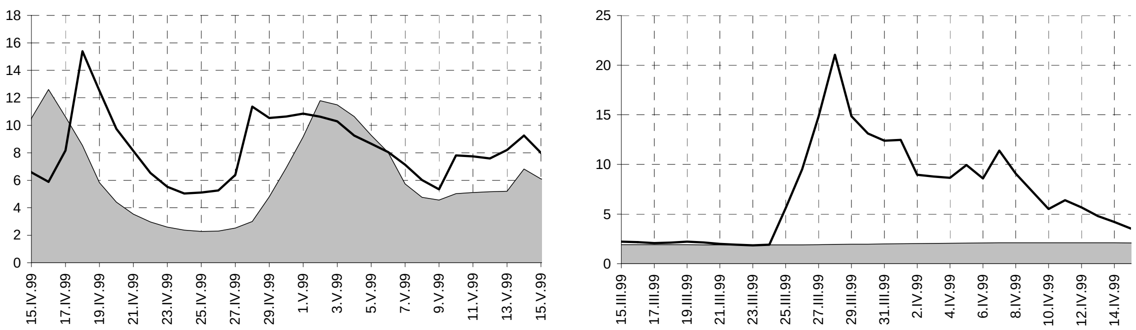

Figure 4: Comparison of the measured runoff values (lines) and simulated baseflow (grey areas) – all in [mm]; left – the Jalovecky Creek catchment, right – the Uhlirska catchment.

4.2. Isotopic runoff separations

Isotopic runoff separations in both catchments showed that the old (pre-event) water significantly contributed to total catchment runoff. Old water contributions in the Uhlirska catchment varied between 40 and 97% (Figure 5). As shown in the Jalovecky Creek catchment, the old water contributions at the beginning of the snowmelt were higher than during the main snowmelt period (Figure 6). Continuous hydrograph separations using the method of averages provided reasonable results for the rain-free periods.

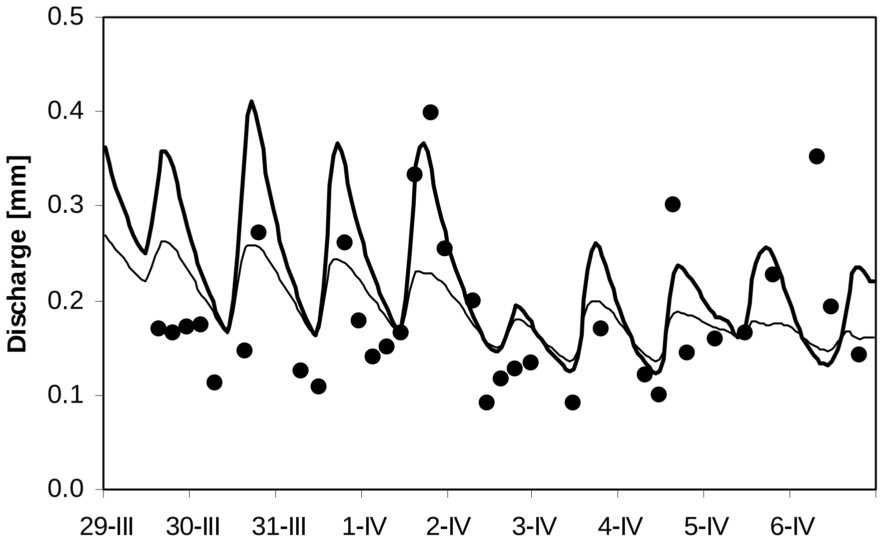

Figure 5: Total catchment runoff (bold line), separated contributions of old water (black circles) and continuous estimation of old water contribution (thin line) in the Uhlirska catchment.

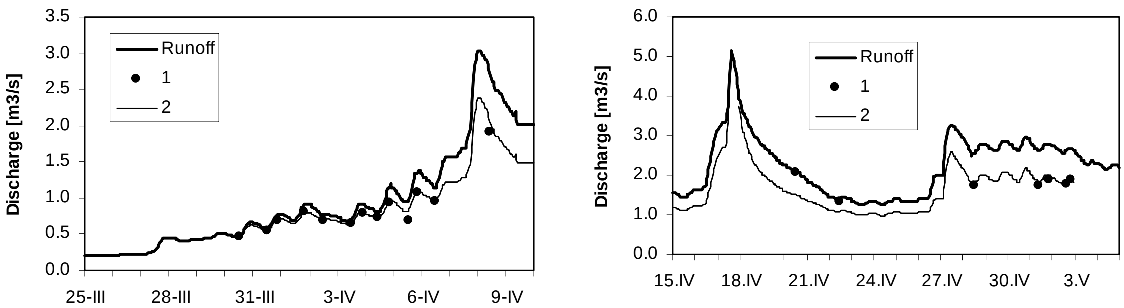

Figure 6: Total catchment runoff (bold line), separated contributions of old water (black circles) and continuous estimation of old water contribution (thin line) in the Jalovecky Creek catchment at the beginning (left) and end of snowmelt (right).

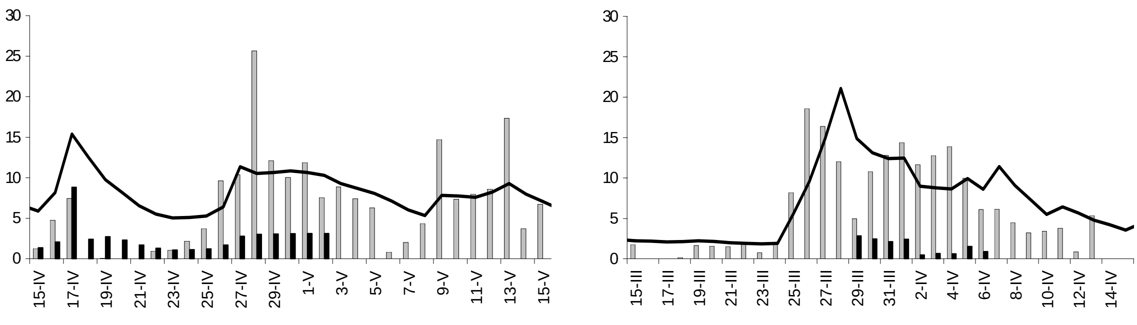

Figure 7: Comparison of the measured runoff values (line), melt water outflow from the snow cover (grey columns) and the new water contributions (black columns), all values in [mm]; left – the Jalovecky potok Creek catchment, right – the Uhlirska catchment.

5. DISCUSSION AND CONCLUSIONS

Isotopic runoff separations provided additional information to the results of hydrological modelling. The WaSiM hydrological model provided reasonable results on the mean snow water contents in both catchments. However, there is a big jump from the correct modelling of the snow water content to achieving the correct results with catchment runoff generation. Modelling and hydrograph separations in the Jalovecky Creek catchment provided convergent results with respect to the role of subsurface runoff in the generation of catchment runoff. Modelled baseflow was only a minor component of the total catchment runoff in the Uhlirska catchment. At the same time, isotopic separation confirmed dominant contributions from old water.

The comparison of measured runoff, modelled outflow from melting snow and the new water contributions derived from isotopic separation (Figures 7 and 8) provided the following results:

In the Jalovecky Creek catchment, outflow from melting snow is similar to the new water contributions until the peak of the snowmelt season. Later, the water from melting snow seems to be stored within the catchment. In the Uhlirska catchment, the outflow from melting snow was almost the same as the total catchment runoff while the new water contributions remained relatively stable. We hypothesise that the old water was extracted from the peaty soils around the stream by the large amounts of water from melting snow.

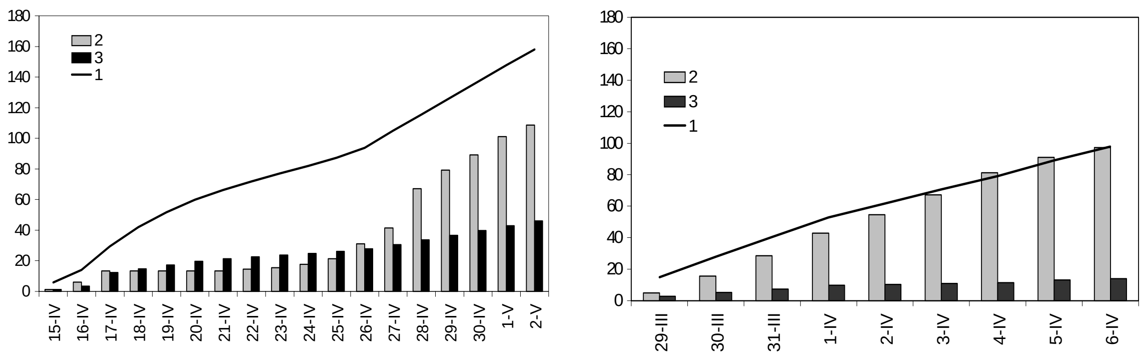

Figure 8: Cumulative runoff (1), melt water outflow from the snow cover (2) and the new water contributions (3), all values in [mm]; left the Jalovecky potok Creek catchment, right the Uhlirska catchment.

ACKNOWLEDGEMENT

This study was supported by grant VEGA2/7149/20. We are greatly indebted to Dr. W. Stichler and Dr. T. Vitvar for the help with isotopic analyses.

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Reliability analysis of a water-quality model considering uncertainty in the model parameters

Manache, G.[1], W. Bauwens[1] & C.S. Melching[2]

[1] *Chair of Hydrology and Hydraulic Engineering, Free University of Brussels (VUB) Pleinlaan 2, 1050 Brussels, Belgium*
[2] *Department of Civil and Environmental Engineering, Marquette University P.O. Box 1881, Milwaukee, Wisconsin 53201-1881, USA*

ABSTRACT

Decisions about water-pollution control and management often are based on predictions made by water-quality models. Many uncertainties are associated with the development and calibration of such models, and, thus, affect the model predictions. Therefore, it often is necessary to perform a reliability analysis prior to model application to water-pollution control and planning problems. In this paper, only the effect of parameter uncertainties on model prediction is investigated by applying sensitivity and uncertainty analyses. Latin Hypercube Simulation in combination with regression and correlation analyses has been used for the DUFLOW model developed for the Dender River in Belgium. These analyses aim to i) identify the model parameters that significantly affect the model-output uncertainty, ii) define the variables that should be measured for improved model calibration, and iii) examine how model sensitivity changes with the level of waste treatment. The results obtained indicate that 3 parameters related to the algal-growth process have the greatest effect on the uncertainty of the simulated dissolved oxygen concentrations in the Dender River.

1. INTRODUCTION

The water-quality model DUFLOW (DUFLOW, 1992) is used to simulate flow and water-quality variables in the Dender River on the basis of the data collected in a previous study (Demuynck *et al*., 1997). The model is calibrated to the available water-quality measurements such as dissolved oxygen (DO), biochemical oxygen demand (BOD), ammonia, and nitrate concentrations at three locations along the Dender River for the period 26 August-15 December 1994. Because the model was calibrated to limited data obtained during a single season, a reliability analysis of the model is necessary before its application as a decision-making tool for water-pollution management in the Dender River.

The goal of this paper is to present the application of reliability analysis to the calibrated DUFLOW model considering uncertainties in the model parameters. This analysis allows determination of the key sources of uncertainty/most sensitive parameters that affect model-prediction uncertainty.

2. LATIN HYPERCUBE SIMULATION (LHS) TECHNIQUE

Melching (1995) summarises some of the techniques that have been used for sensitivity and uncertainty analyses on computer models in water-resources engineering. Several studies on the relative performance of the various techniques indicate that Monte Carlo (MCS) and Latin Hypercube Simulation (LHS) are very powerful, robust, and flexible as compared to the other methods. For models with high computational requirements, like the one used in this study, it is best to use the LHS technique, which provides the flexibility of MCS with less computational load.

The LHS technique (McKay *et al*., 1979; McKay, 1988) is a type of stratified Monte Carlo sampling. In this technique, the range of each of the K variables included in the uncertainty analysis $X_1, X_2, ..., X_k$ is divided into N intervals in such a way that the probability of the variable falling in any of the intervals is 1/N. One value is selected at random from each interval. The N values obtained for the first variable X_1 are paired randomly with the N values of the second variable X_2. These pairs are furthermore randomly combined with the sampled values of the third variable etc., which finally results in N combinations of K variables. This set of K-tuples is the Latin Hypercube sample that is used for successive execution of model runs.

When using LHS, the variable space is sampled with few samples, thus, the number of model runs can be small. Aalderink *et al*. (1995) used about 100 runs with the LHS technique in their uncertainty analysis on a heavy metal model. McKay (1988) suggests that a number of simulation runs N equal to twice the number of uncertain parameters (K) might provide a good balance of accuracy and computational cost for models with a large number of parameters. Iman & Helton (1985) indicate that a choice of N equal to 4/3.K usually gives satisfactory results. Therefore, in this study, the number of simulations is taken equal to 4/3.K. This assumption was verified by making another set of simulations with N = 3.K.

Several computer packages containing routines for MCS and LHS methods are available. In this study, The UNCSAM computer package developed by the Dutch Institute for Public Health and the Environment, (Janssen *et al.,* 1992) was used to generate the sets of random model parameters using the LHS technique and also to perform the various regression and correlation analyses among input parameters and model output used to indicate key parameters affecting output uncertainty.

3. DESCRIPTION OF THE DENDER RIVER

The Dender River is a tributary of the River Scheldt. Its total drainage area is about 1,384 km^2. The Dender River is characterised by very irregular discharges; high discharges in winter, up to 100-150 m^3s^{-1}, and low discharges in summer, lower than 1 m^3s^{-1}. The average discharge at the mouth is about 10 m^3s^{-1} (Demuynck *et al.,* 1997). For navigation purposes, the river has been canalised and regulated by several hydraulic structures such as ship locks and sluices.

Several sources of pollution contribute to water-quality problems of the Dender River. The domestic loads coming from about 300.000 inhabitants constitute the major source of pollution. Eighty four percent of the wastewater is collected by a sewer system but only about twelve percent is treated. In addition to urban sources, the river receives industrial wastewater and diffuse pollution caused by the extensive use of chemicals and organic fertilisers and pesticides in agricultural activities.

During dry periods, the high pollutant loads combined with low flow velocity and low discharges result in negative impacts on the water quality in the river. In the downstream part, the aquatic life is seriously disrupted and the river is considered biologically dead. The construction of wastewater treatment plants along the river in recent years together with the dilution effect during winter (wet period) has lead to improvement in the water quality of the river. However, during dry periods, the basic water flow is not always sufficient to cope with the remaining pollution.

4. THE DUFLOW MODEL

DUFLOW is a computer package for simulating one-dimensional unsteady flow and water quality in open water courses (DUFLOW, 1992). In the water quality part, two pre-defined eutrophication models are available. However, process description also can be supplied by the users and this concept makes DUFLOW a very flexible package with which different types of water-quality models can be developed.

In DUFLOW, a 51-km stretch of the Dender River between Deux-Acren and Dendermonde is divided into 48 elements. Hydraulic structures such as sluices or ship locks are represented in the model as control elements. Cross sections measurements at 22 points and length profiles are used to describe the geometry of the river.

In this study, EUTROF1, one of the two pre-defined eutrophication models included in DUFLOW, is used to simulate water quality. Constituents that can be simulated in Eutrof1 are DO, BOD, algal biomass, components of the nitrogen cycle (organic nitrogen, ammonia, nitrate), components of phosphorous cycle (organic and inorganic phosphorous), and suspended solids.

Discharges and pollutant loads are represented in two ways, constant loads and time varying loads. Effluent sources from industries, households, and wastewater treatment plants are considered to have a constant value for the entire simulation period and are added to the river at 20 points. Effluent sources coming from agricultural activities are added to the system at 10 points and are given as time series for the considered simulation period. Discharges and pollutant concentrations, for the upstream boundary, also are given as time series that cover the entire simulation period.

5. SENSITIVITY AND UNCERTAINTY ANALYSES APPLIED TO THE DUFLOW MODEL

The DUFLOW model was calibrated to the available measurements of DO, BOD, ammonia, and nitrate concentrations at three places along the Dender River: Geraardsbergen, Denderleeuw and Denderbelle for the period 26 August-15 December 1994. Because the calibration period is short and covers only one season of the year and taking into account the errors in the input data (hydraulic characteristics, discharges, loads, boundary conditions, etc.) it is likely that the set of calibrated parameters cannot be considered unique and conceptually realistic to assure good results when the DUFLOW model is applied under different conditions than those related to the calibration period.

Table 1: The mean values, coefficients of variation, maximum and minimum limits, and distribution types used for the Latin Hypercube generation of the DUFLOW parameters.

Parameter	Definition	Mean	COV	Min	Max	Distribution
achlc	Chlorophyll to carbon ratio	30		10	100	Triangular
anc	Nitrogen to carbon ratio	0.16		0.05	0.43	Triangular
aoc	Oxygen to carbon ratio	4	0.5			Normal
apc	Phosphorus to carbon ratio	0.025		0	0.05	Triangular
e0	Background extinction	1.7		1	5	Triangular
ealg	Specific extinction chlorophyll	0				Constant
ess	Specific extinction suspended solids	0				Constant
fbod	Fraction dissolved BOD	0.4	0.45			Normal
fdnorg	Fraction dissolved organic nitrogen	0				Constant
fdporg	Fraction dissolved organic phosphorus	0				Constant
fnorg	Fraction norg released by respiration	1				Constant
fporg	Fraction porg released by respiration	1				Constant
is	Optimal light intensity	80		10	100	Triangular
kbod	Oxidation rate constant bod	0.4	0.25			Normal
kbodo	Monod constant oxidation bod	2	0.25			Normal
kden	Denitrification rate constant	0.1	0.25			Normal
kdie	Die rate constant	0.2		0.003	0.8	Triangular
kdno	Monod constant denitrification	0.5	0.2			Normal
kmin	Rate constant mineralization	0.65	0.25			Normal
kmn	Ammonia preference factor	0.025				Constant
kn	Monod constant nitrogen	0.1	0.2			Normal
knit	Nitrification rate constant	0.2	0.25			Normal
kno	Monod constant nitrification	2	0.2			Normal
kp	Monod constant phosphorus	0.014		0.001	0.05	Triangular
kpip	Phosphorus partition coefficient	0.01				Constant
kres	Respiration rate constant	0.15		0.05	0.2	Triangular
krmin	Constant of O'Connor-Dobbins equation	3.94	0.2			Lognormal
tbod	Temperature coefficient oxidation BOD	1.045	0.05			Normal
tden	Temperature coefficient denitrification	1.045	0.05			Normal
tga	Temperature coefficient algal growth	1.047	0.05			Normal
tmin	Temperature coefficient mineralization	1.047	0.05			Normal
tnit	Temperature coefficient nitrification	1.088	0.05			Normal
tra	Temperature coefficient algal respiration	1.047	0.05			Normal
trea	Temperature coefficient reareation	1.016	0.05			Normal
umax	Maximum algal growth rate	4	0.2			Normal
vs0	Nett settling velocity organic matter	1.5	0.25			Normal
vss	Settling velocity suspended solids	0.1	0.25			Normal

Within the DUFLOW model, 37 water-quality parameters have been used for modelling the water-quality processes in the Dender River. Twenty-nine parameters were considered uncertain, while the other eight parameters are assumed to have a small effect on the model uncertainty. For the application of the LHS procedure, each of these 29 parameters has been assigned a probability distribution specified by the mean, the coefficient of variation and, in some cases, maximum and minimum limits of the parameter range. Since the DUFLOW model was already calibrated, distributions with a central tendency were used (normal, log-normal or triangular) with distribution mean values estimated equal to the calibrated parameter values. The mean value, coefficient of variation, maximum and minimum limits, and distribution type used for the LHS generation of the parameters are listed in Table 1.

The software package UNCSAM (Janssen *et al*., 1992) was used to generate the N sets of the random parameters values corresponding to the LHS procedure. N is taken equal to 4/3 times the number of the uncertain parameters resulting in 40 combinations of 29 parameters. The DUFLOW model has been executed successively with the different sets of generated parameters to simulate DO, BOD, ammonia, and algal biomass concentrations in each of the 48 sections in the Dender River.

Table 2: The values and rankings of various sensitivity/uncertainty measures calculated on the amount of time during which the DO concentrations are less than 2 mg l^{-1} at Denderleeuw for simulated current conditions.

Param-	**Latin Hypercube Simulation results**													
eter	**RTU**	**rank**	**SRC**	**rank**	**SPC**	**rank**	**LCC**	**rank**	**SRRC**	**rank**	**SPRC**	**rank**	**LRCC**	**rank**
Is	0.56	1	0.49	1	0.44	1	0.61	1	0.34	4	0.30	4	0.46	1
e0	0.42	2	0.44	2	0.42	2	0.40	3	0.35	3	0.34	3	0.33	3
Kdie	0.41	3	0.38	3	0.35	3	0.41	2	0.45	1	0.42	1	0.42	2
Umax	0.28	4	-0.21	6	-0.19	6	-0.30	4	-0.38	2	-0.35	2	-0.31	4
Aoc	0.24	5	0.23	4	0.21	4	0.24	5	0.17	9	0.16	10	0.20	10
Fbod	0.22	6	0.22	5	0.19	5	0.20	6	0.03	23	0.03	24	0.10	17
Kres	0.21	7	0.15	8	0.14	8	0.18	7	0.11	13	0.10	13	0.15	12
Kdno	0.16	8	-0.13	10	-0.12	10	-0.18	8	-0.04	19	-0.04	19	-0.04	21
Kmin	0.15	9	-0.19	7	-0.18	7	-0.11	12	-0.02	28	-0.02	28	0.02	26
Tmin	0.15	10	-0.14	9	-0.13	9	-0.13	11	-0.03	22	-0.03	22	-0.02	27
Kbodo	0.14	11	-0.11	11	-0.09	12	-0.14	9	-0.27	6	-0.21	6	-0.23	7
Tden	0.13	12	-0.10	12	-0.09	11	-0.14	10	-0.06	17	-0.06	17	-0.10	16
Trea	0.12	13	0.06	18	0.05	19	0.10	14	0.04	21	0.03	21	0.12	14
Tnit	0.11	14	0.06	19	0.06	18	0.10	13	-0.02	26	-0.02	26	-0.09	18
Kp	0.10	15	0.07	16	0.07	16	0.09	15	-0.05	18	-0.04	18	0.04	22
Kn	0.10	16	0.09	14	0.08	13	0.04	22	-0.01	29	-0.01	29	0.03	25
Anc	0.08	17	-0.02	26	-0.02	26	0.02	27	-0.13	12	-0.12	12	0.00	29
Krmin	0.07	18	-0.03	22	-0.03	22	-0.01	29	-0.17	10	-0.16	9	-0.21	9
Kno	0.07	19	-0.09	15	-0.08	14	0.04	21	-0.07	16	-0.06	16	0.01	28
Tga	0.06	20	-0.01	29	-0.01	29	0.03	24	0.03	25	0.02	25	0.04	23
Knit	0.06	21	0.04	21	0.04	21	0.05	20	0.29	5	0.27	5	0.21	8
Kden	0.06	22	-0.05	20	-0.05	20	-0.05	19	-0.09	14	-0.08	14	-0.08	19
vs0	0.06	23	0.07	17	0.06	17	0.03	23	-0.02	27	-0.02	27	-0.13	13
Kbod	0.06	24	0.03	25	0.02	25	0.09	16	0.20	8	0.19	7	0.27	5
Apc	0.06	25	-0.03	23	-0.02	23	0.01	28	-0.09	15	-0.08	15	-0.06	20
Tbod	0.04	26	0.02	27	0.02	27	-0.06	18	-0.04	20	-0.04	20	-0.23	6
Vss	0.03	27	0.09	13	0.08	15	-0.07	17	-0.22	7	-0.19	8	-0.17	11
Tra	0.03	28	0.03	24	0.02	24	-0.03	25	-0.14	11	-0.14	11	-0.10	15
Achlc	0.02	29	0.02	28	0.02	28	-0.02	26	-0.03	24	-0.03	23	-0.03	24

The sensitivity and uncertainty analyses (SA/UA) are restricted to DO because its concentration generally is considered as the primary indicator of aquatic-system health. The

SA/UA is performed on the amount of time that DO concentrations are less than a specified value (2 mg l^{-1}, 3 mg l^{-1}, and 4 mg l^{-1}) over a period of one year (1990). Two locations on the Dender River are considered for model analysis: Denderleeuw and Denderbelle. These represent the locations where low DO concentrations (<4 mg l^{-1}) occur for more than 80% and 96% of the time, respectively, under current conditions.

To examine the effect of pollution reduction on the model sensitivity, the application of SA/UA to the DUFLOW model output is done for two cases: i) current conditions where only 12% of the waste flow is treated and ii) future conditions according to the wastewater sanitation scenario (AWP-II) proposed by the Flemish Government. The pollution abatement plan AWP-II considers a removal of about 90% of BOD, 44% of nitrogen, and 75% of phosphorus with reference to the pollutant loads considered for the current situation.

Table 3: The values and rankings of various sensitivity/uncertainty measures calculated on the amount of time during which the DO concentrations are less than 2 mg l^{-1} at Denderleeuw for simulated future conditions according to AWP-II water sanitation scenario.

Param-	**Latin Hypercube Simulation results**													
eter	**RTU**	**rank**	**SRC**	**rank**	**SPC**	**rank**	**LCC**	**rank**	**SRRC**	**rank**	**SPRC**	**rank**	**LRCC**	**rank**
Kdie	0,47	1	0,47	1	0,44	1	0,46	1	0,52	1	0,50	1	0,53	1
e0	0,46	2	0,46	2	0,43	2	0,46	2	0,34	2	0,32	2	0,38	2
Is	0,42	3	0,42	3	0,41	3	0,41	3	0,30	3	0,28	3	0,25	6
Aoc	0,27	4	0,25	4	0,24	4	0,27	5	0,28	5	0,27	5	0,30	3
Umax	0,26	5	-0,24	5	-0,23	5	-0,28	4	-0,27	6	-0,25	6	-0,26	5
Knit	0,19	6	0,15	8	0,14	8	0,22	6	0,18	9	0,17	9	0,20	8
Vss	0,18	7	0,16	7	0,15	7	0,17	9	-0,04	21	-0,04	21	-0,01	28
Kbod	0,17	8	0,14	11	0,13	11	0,19	7	0,29	4	0,27	4	0,28	4
Kden	0,17	9	-0,14	12	-0,13	12	-0,18	8	-0,04	19	-0,04	20	-0,07	20
Kno	0,16	10	-0,14	10	-0,14	10	-0,16	10	0,01	29	0,00	29	-0,06	22
Trea	0,15	11	0,12	14	0,12	14	0,16	11	0,20	7	0,19	8	0,25	7
Kres	0,14	12	0,13	13	0,13	13	0,15	12	0,08	16	0,08	16	0,17	10
Tra	0,13	13	0,21	6	0,20	6	0,04	22	-0,01	28	-0,01	28	-0,12	16
Tbod	0,11	14	-0,09	17	-0,09	16	-0,11	13	-0,14	11	-0,13	11	-0,16	13
Apc	0,11	15	-0,14	9	-0,14	9	-0,04	19	-0,02	26	-0,02	26	0,03	25
Kmin	0,10	16	0,08	19	0,08	19	0,08	15	0,10	13	0,09	13	0,18	9
Kn	0,08	17	0,04	23	0,04	23	0,11	14	0,13	12	0,12	12	0,16	12
vs0	0,08	18	-0,10	16	-0,09	17	-0,04	23	-0,14	10	-0,13	10	-0,16	11
Tden	0,07	19	-0,05	22	-0,05	22	-0,03	24	-0,01	27	-0,01	27	0,00	29
Kp	0,07	20	-0,06	21	-0,06	21	-0,05	18	-0,08	15	-0,08	15	-0,04	24
Tga	0,07	21	0,03	25	0,03	25	0,08	16	-0,04	22	-0,03	22	-0,02	26
Tnit	0,06	22	-0,11	15	-0,10	15	-0,03	26	-0,04	20	-0,04	19	0,01	27
Anc	0,06	23	0,06	20	0,06	20	0,04	21	0,07	17	0,06	17	0,07	21
Krmin	0,06	24	-0,08	18	-0,08	18	0,01	28	-0,20	8	-0,19	7	-0,15	15
Achlc	0,06	25	-0,03	26	-0,02	26	-0,07	17	-0,09	14	-0,09	14	-0,16	14
Fbod	0,06	26	-0,04	24	-0,03	24	-0,02	27	0,02	25	0,02	25	0,07	19
kdno	0,04	27	0,00	29	0,00	29	0,03	25	-0,03	24	-0,03	24	-0,05	23
kbodo	0,04	28	-0,02	27	-0,02	27	-0,04	20	-0,03	23	-0,03	23	-0,09	17
tmin	0,03	29	0,01	28	0,01	28	-0,01	29	0,06	18	0,06	18	0,08	18

The sensitivity and uncertainty contribution of the model parameters may be quantified by various measures. Most of them are based on regression and correlation analyses such as the root of uncertainty (RTU), the standardised regression coefficient (SRC), the standardised rank regression coefficient (SRRC), the semi-partial correlation coefficient (SPC), the linear correlation coefficient (LCC), the semi-partial rank correlation coefficient (SPRC), and the linear rank correlation coefficient (LRCC). The definitions of these measures can be found in Janssen *et al.* (1992). These measures were used to rank the importance of the uncertain DUFLOW parameters on the uncertainty in the selected model output at the two considered locations on the Dender River. The values and rankings of various SA/UA measures calculated on the amount of time during which the DO concentrations are less than 2 mg l^{-1} at Denderleeuw are given as an illustration for the simulated current conditions (Table 2) and for the pollution abatement scenario AWP-II (Table 3).

To determine the most important DUFLOW parameters based on the LCC and LRCC measures, a simple test defined by Yevjevich (1971, p. 238) has been applied. For the sample size used in this study (N=40 simulations), the 95% confidence bound for correlation coefficients being significantly different from zero r_B is ±0.312.

6. RESULTS AND DISCUSSION

The results obtained from the LHS analysis indicate the following:

- Only three parameters have a significant effect on the amount of time during which the DO concentrations are less than the specified value: the optimal light intensity (is), the background extinction (e0), and the die-rate constant (kdie). These parameters are mainly used in modelling the algal-growth process.
- For the different DO levels taken into consideration (2 mg l^{-1}, 3 mg l^{-1}, and 4 mg l^{-1}), it can be noticed that the previously mentioned parameters are the most significant. The only difference is that the ranking varies with to the considered DO level and also with to the SA/UA measure used for the ranking.
- For the two selected locations (Denderleeuw and Denderbelle) on the Dender River that are considered for model analysis, the results are similar and the same parameters have been identified to be most influential on the model-output uncertainty.
- For the AWP-II scenario, SA/UA indicate that for the considered DO concentrations and river locations, the same parameters have been found to have a significant effect on output uncertainty as for the current conditions.

It can be concluded that algal processes dominate the uncertainty in simulated DO concentrations in the Dender River. Taking into consideration that the calibration period of the DUFLOW model was limited to the Fall where algal activity is small and no chlorophyll data were available to calibrate the algal process, it is suggested that:

- The DUFLOW model applied to the Dender River should be recalibrated by giving more attention to the sensitive parameters determined in this study e0, is, and kdie, so that the uncertainty in the simulated DO concentrations can be reduced.
- In order to better identify the algal process parameters, the DUFLOW model should be calibrated to Chlorophyll-a concentrations in the Dender River especially for the period during which high algal activity occurs (spring and summer). Therefore, field measurements of Chlorophyll-a concentrations need to be done.

Applications of reliability and uncertainty analysis may reveal similarly important insight for other water-quality modelling efforts.

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Conference on “Monitoring and Modelling Catchment Water Quantity and Quality”
Ghent, Belgium, September 27-29, 2000

Extreme runoff simulation in the Mala Svinka Basin

Miklanek, P., D. Halmova & P. Pekarova

Institute of Hydrology SAS
P.O. Box 94, 838 11 Bratislava 38, Slovak Republic
Email: miklanek@uh.savba.sk, halmova@uh.savba.sk, pekarova@uh.savba.sk

ABSTRACT

In the first part of this paper, the catastrophic flood that occurred on 20 July 1998 in the Mala Svinka basin (61.21 km^2) in the north–eastern part of Slovakia is analysed. Several settlements were damaged during this disaster and 47 people died. Empirical methods, based on field measurements made after the flood, were used to estimate both the rainfall amount and the peak flows. It is assumed that in the core of the storm the rainfall was 120 mm over a period of 45–60 minutes. The return period of the flood was estimated as being considerably longer than 1000 years. In the second part of the contribution the AGricultural Non-Point Source Pollution (AGNPS) model was used to simulate the flood wave for rainfall depths between 70 and 120 mm. The simulation used two separate versions of the AGNPS model: i) for the whole basin, and ii) for the upper part of the basin. .

1. INTRODUCTION

In the second half of the 1990s several catastrophic floods occurred in Slovakia and across Central Europe. It appears from this that the frequency of flash floods is increasing. According to data from the Hydrological Information and Forecasting Service of the Slovak Hydrometeorological Institute, the number of days with a water level higher than that corresponding to the first stage of the flood warning has been increasing on Slovak rivers in the 1990s. Similarly, the Ministry of the Agriculture of the Slovak Republic has reported a similar tendency in costs due to flood damage.

The most catastrophic rainstorm flash-flood in the history of Slovakia occurred in the Mala Svinka basin on 20 July 1998 (Svoboda & Pekarova, 1998; Halmova, 1998). Forty-seven people died during the flood, which also caused considerable material damage.

The estimated rainfall depth of over 100 mm during one hour is not, however, the highest in the history of meteorological observations in Slovakia. According to Samaj *et al.* (1985), in Salka, a total of 232 mm was recorded on 12 July 1957 during a storm of 65 minutes duration, and 162.8 mm was recorded in Trnava on 3 June 1951 over 2 hours. Neither of these storms produced historical floods.

The purpose of this paper is to:

- describe the Mala Svinka basin in the context of the flood on 20 July 1998, and
- simulate the floodwave using the AGNPS model, with distributed parameters for rainfall depths between 70 and 120 mm.

2. MALA SVINKA BASIN AND THE CATASTROPHIC FLOOD ON 20 JULY 1998

Mala Svinka basin is situated in the Bachuren Mountains (1081 m.a.s.l.) in Eastern Slovakia. The source of the stream is a spring at 920 m.a.s.l. and the confluence with the Svinka River is at 320 m.a.s.l. The length of the stream is 23.7 km and the area of the basin is 61.21 km^2. The basic characteristics of the basin are given in Table 1. The layout of the basin is on Figure 1, showing a narrow and feather-shaped valley. The basin is in an area of Neogene flysh (flysh is a geological formation consisting of alternating layers of sandstones and clay). The shallow soils and steep slopes result in severe erosion.

Table 1: Basic morphometric characteristics of subbasins of Mala Svinka catchment.

River Cross-section	Area [km^2]	Length [km]	A/L^2	Forest Cover [%]	River slope [%]	Q_{100} [m^{3}s^{-1}]	Min elevation [m.a.s.l]
Rencisovsky brook Rencisov	7.07	4.6	0.334	20	8.8	54.54	600
Mala Svinka Downstream Rencisov	12.52	4.7	0.567	60	7.6	63.5	600
Mala Svinka Upstream Uzovske Peklany	21.53	8.2	0.320	60	5.2	78.25	514
Mala Svinka Jarovnice	34.39	13.8	0.181	50	3.8	92.55	410
Mala Svinka Outlet	61.21	23.7	0.109	40	2.4	111.42	330

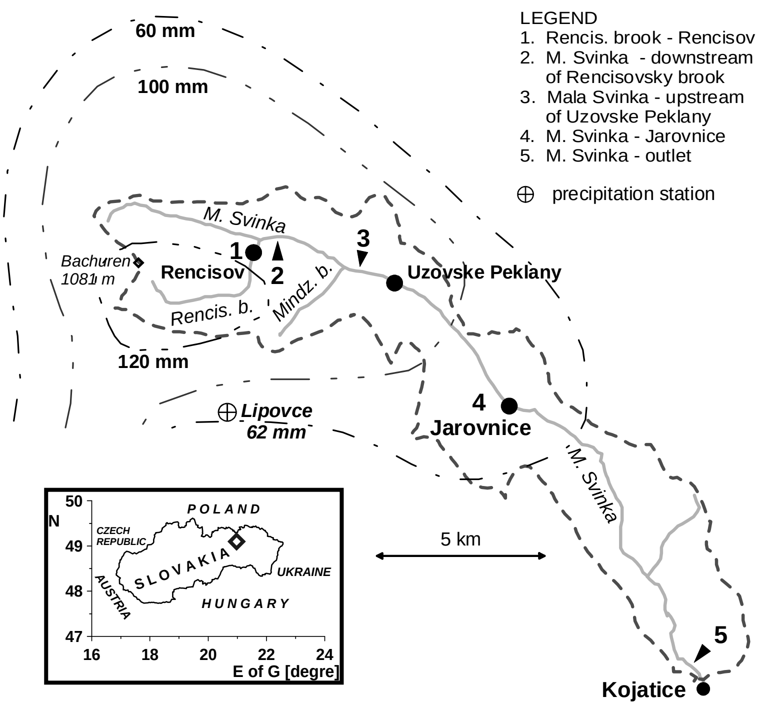

Figure 1: Mala Svinka basin, rainfall depth on 20 July 1998.

According to Shmu (1963), the basic mean annual water balance elements in 1930–1961 were as follows: precipitation 648 mm, runoff 152 mm, and evaporation 496 mm. The mean discharge over the same period was 0.30 m^3 s^{-1}.

2.1. Rainfall

In Slovakia, the mean rain gauge density is about 1 gauge per 70 km^2 but unfortunately, there is no rain gauge in the Mala Svinka basin. However, there are eight rain gauge stations situated around the basin. The nearest station at Lipovce, about 5 km far from the drainage basin (see Figure 1), recorded only 62 mm during the day of the flood.

Major rainfall depths have been measured in Lipovce on several occasions: 81 mm fell on 25 July 1965 during the afternoon, 70 mm on 13 July 1973, and 93 mm on 4 August 1997 between 18:00 and 19:00 CET. The highest daily rainfall in the neighbouring basins was 97.4 mm, gauged on 29 June 1958 in Brezovica nad Torysou. No significant flood was produced by these extreme rainfalls.

Fasko & Lexmann (1998) noted that the 62 mm of rain in Lipovce represented the 10-year return period. They also estimated that a rainfall depth of over 100 mm occurs with a probability of 200 years. Samaj *et al*. (1985) estimated the N-year maximum daily rainfall depths at the Brezovica nad Torysou station (Table 2).

Table 2: N-years maximum daily precipitation [mm] in Brezovica nad Torysou.

Station / Years	2	5	10	20	30	50	80	90	100	200
Brezovica nad Torysou	37.8	51.6	60.5	69.7	74.9	81.1	87.0	88.6	90.0	98.3

According to Stastny (1998), the rainfall depths and intensities over the upper part of the Mala Svinka basin were significantly higher than this. They were estimated from meteorological and radar observations as 100 mm h^{-1}, and, as the duration of the storm was approximately 1 h, this suggested a total depth of more than 100 mm for 20 July 1998. The approximate isohyets (according to Fasko & Lexmann, 1998) are drawn on Figure 1. Several critical factors coincided in the area of Mala Svinka basin to produce the flood: i) saturation of the catchment by previous precipitation; ii) high precipitation; iii) low retention capacity and hydrogeological structure of the area.

2.2. Runoff

There is no streamflow gauging station in the basin. It was therefore very difficult to estimate either the peak runoff or the shape of the flood hydrograph.

A team from the Institute of Hydrology SAS visited the catchment three weeks after the disaster to measure the pertinent characteristics that would allow hydraulic calculations of peak flows. Three cross-sections were studied that had remained undisturbed since the flood occurrence, and still had distinct traces of the highest water level. The flood peak flows were reconstructed for each of the measured cross-sections, using data on longitudinal slopes, and estimates of Manning roughness coefficients.

The peak discharge estimated in Profile 1 (Rencisovsky Brook) was 112.5 m^3s^{-1}. The discharge of the Mala Svinka upstream of the confluence with Rencisovsky Brook was 37.9 m^3s^{-1}, and therefore the peak discharge at Profile 2 can be estimated as 150.4 m^3s^{-1}, based on field measurements.

Svoboda & Pekarova (1998) estimated the peak flows by NLC (Non-Linear Cascade) model, and Majercakova *et al.* (1998) used empirical relations based on rainfall intensity. The selected results in the same profiles as in this study are shown in Table 3.

Table 3: Peak discharges estimated by other methods and authors.

	Measured [m³s⁻¹]	**Svoboda & Pekarova (1998) [m³s⁻¹]**	**Majercakova *et al*. (1998) [m³s⁻¹]**
Profile 1	112.6	112.0	95.0
Profile 2	150.4	136.0	140.0
Profile 3	-	-	190.0
Profile 4	-	178.7	230.0
Profile 5	-	-	-

The disastrous character of the flood is obvious from the fact that the mean long term discharge in Profile 5 was 0.30 m^3s^{-1} between 1930 and 1961, and the 100-year flood in the same profile was estimated for the same period as 80 m^3s^{-1} (Shmu, 1963). Majercakova *et al*. (1998) estimated the July 1998 flood as exceeding the 1000-year flood in all the profiles within the Mala Svinka basin. It is interesting that the same flood in the recipient River Torysa, at Sabinov station (catchment area 495 km^2) corresponds only to the 1-year flood.

Table 4: Simulated peak flows Q, yields q_{max}, flood wave volumes V and runoff depth R in selected profiles. Simulations were done i) in the whole basin, and ii) in the upper part of the basin for rainfall P between 70 and 120 mm.

			Profile 1		**Profile 2**		**Profile 3**		**Profile 5**	
		Area [km²]	**6.7**		**12.52**		**21.53**		**61.21**	
P			**i)**	**ii)**	**i)**	**ii)**	**i)**	**ii)**	**i)**	**ii)**
70	Q	[m^3s^{-1}]	59	57	92	79	124	100	222	
	q_{max}	[$m^3s^{-1}km^{-2}$]	8.8	8.5	7.4	6.3	5.8	4.6	3.6	
	V	[10^3 m^3]	382	328	696	598	1197	957	3250	
	R	[mm]	54	49	56	48	53	44	53	
80	Q	[m^3s^{-1}]	68	67	107	93	145	119	261	
	q_{max}	[$m^3s^{-1}km^{-2}$]	10.1	9.9	8.5	7.4	6.7	5.5	4.3	
	V	[10^3 m^3]	450	391	820	712	1413	1149	3856	
	R	[mm]	64	58	66	57	63	53	63	
90	Q	[m^3s^{-1}]	78	76	122	106	166	136	300	
	q_{max}	[$m^3s^{-1}km^{-2}$]	11.6	11.3	9.7	8.5	7.7	6.3	4.9	
	V	[10^3 m^3]	519	448	942	814	1631	1324	4444	
	R	[mm]	73	67	75	65	72	61	73	
100	Q	[m^3s^{-1}]	88	88	137	124	188	161	339	
	q_{max}	[$m^3s^{-1}km^{-2}$]	13.1	13.2	10.9	9.9	8.7	7.5	5.5	
	V	[10^3 m^3]	589	528	1065	966	1848	1575	5056	
	R	[mm]	83	79	85	77	82	73	83	
110	Q	[m^3s^{-1}]	97	98	152	138	209	180	377	
	q_{max}	[$m^3s^{-1}km^{-2}$]	14.5	14.6	12.1	11.0	9.7	8.3	6.2	
	V	[10^3 m^3]	658	591	1186	1081	2071	1772	5644	
	R	[mm]	93	88	95	86	92	82	92	
120	Q	[m^3s^{-1}]	107	107	167	150	230	197	416	
	q_{max}	[$m^3s^{-1}km^{-2}$]	16.0	15.9	13.3	12.0	10.7	9.1	6.8	
	V	[10^3 m^3]	739	647	1288	1186	2289	1947	6231	
	R	[mm]	105	97	103	95	102	90	102	

3. SIMULATION OF THE FLOODWAVE USING THE AGNPS MODEL

The hydrological part of the AGNPS model (AGricultural Non-Point Source Pollution Model) was used to simulate the peak flows and runoff depths in Mala Svinka basin. The AGNPS is a geographically oriented model. It models the floodwave, and both water and material flows during a single rainfall-runoff event, using as the main inputs precipitation depth and duration, and giving outputs of the peak flows and runoff depth. The model can be used for simulation of different runoff situations, including dry and wet conditions depending on antecedent precipitation. Details of the model can be found in the manual by Young *et al.* (1996). This model has been used by many authors in Slovakia, e.g. Lichner *et al*. (1999), to study the influence of land use on nutrient fluxes.

4. RESULTS

Using the Slovak Hydrometeorological Institute’s estimates of the rainfall depths for the 20 July 1998 flood event, simulations were run for rainfall depths between 70 and 120 mm, with a step of 10 mm. Unfortunately, the AGNPS model only accepts a uniform value of the rainfall amount for the entire basin, so the upper part of the basin around Rencisov village was simulated separately.

The simulation results in the four profiles are presented in Table 4: 1. Rencisov brook in Rencisov; 2. Mala Svinka downstream Rencisov; 3. Mala Svinka upstream Uzovske Peklany; and 5. Mala Svinka - outlet.

The areal pattern of the peak flow, both for the whole and for part of the Mala Svinka basin has been simulated for 80 mm rainfall, as in Figure 2.

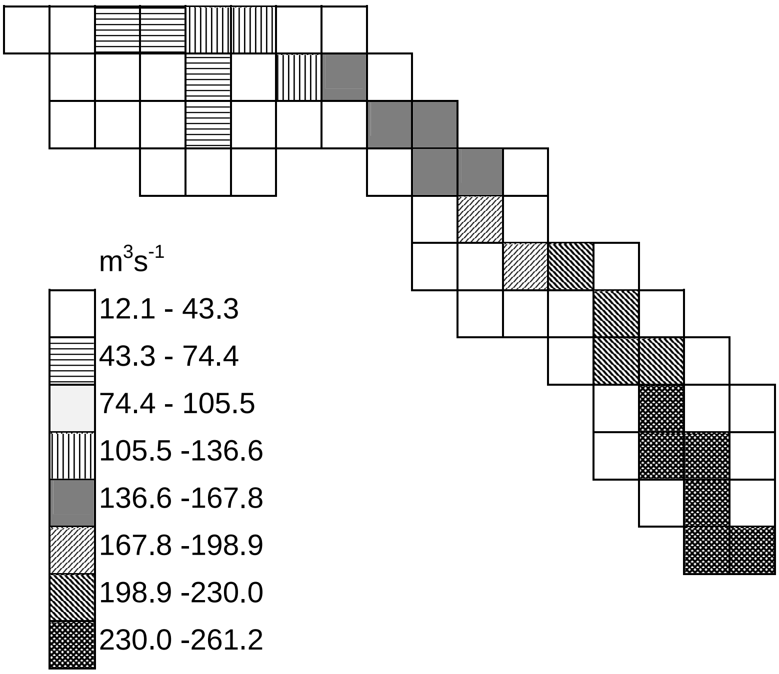

Figure 2: Areal patterns of peak flows in m^3s^{-1}, model AGNPS output in Mala Svinka basin, grid 1x1km, precipitation 80 mm.

5. CONCLUSION

The Mala Svinka basin is ungauged, and therefore the floodwave and the peak flows had to be estimated indirectly and post-event by several authors. Svoboda & Pekarova (1998) and Halmova (1998) simulated the peak flows using different models (but also including AGNPS) with good agreement for estimated flow. Majercakova *et al.* (1998) did a similar analysis using empirical rainfall intensity relations. The Slovak Hydrometeorological Institute estimated the return periods of flood peaks in some of the smaller subcatchments as being considerably longer than 1000 years. The results are summarised in Table 3.

The aim of this paper has been to simulate hypothetical floods in this basin caused by different rainfall intensities. The simulations were based on assumptions of uniform rainfall of the selected intensity over the whole area of the basin. The real situation for the July 1998 flood corresponds approximately to the 110 mm rainfall in the upper area of the basin.

The simulated runoff coefficient in the upper part of the basin for 100 mm rainfall was up to 83%. The corresponding coefficient for 120 mm rainfall was also estimated at up to 87.5%, as it was thought that the rainfall depth was this amount in the core of the storm. It is probably not possible to take precautions for a flood with such an extreme runoff depth concentrated over a small area in such a short time.

The AGNPS model is, in our opinion, a good tool for estimation and analysis of the rainfall-runoff processes in the basin, and exhibits a particularly useful graphical function.

ACKNOWLEDGEMENT

The paper was prepared with support of the VEGA grant 2016.

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Conference on “Monitoring and Modelling Catchment Water Quantity and Quality”
Ghent, Belgium, September 27-29, 2000

Another methodology for a better use of descriptors of ungauged basins in lumped hydrological models

Perrin, C. & C. Michel

Cemagref
Parc de Tourvoie, BP 44, F-92163 Antony Cedex, France
Email: charles.perrin@cemagref.fr

ABSTRACT

The classical way to relate parameters of lumped rainfall-runoff models to catchment descriptors is to use multiple regression type approaches. However, such a method, which is designed to find the best relationship between model parameters and basin attributes, is not theoretically optimal to yield best model performances. An improved methodology is tested to make a better use of the information contained in catchment descriptors. It uses explicitly the hydrological model to determine relationships between parameters and descriptors. The method was applied on a set of 131 catchments, but proved to be only marginally better than the classical method.

1. INTRODUCTION

A specific use of hydrological models designed to simulate rainfall-runoff transformation concerns ungauged catchments where no streamflow data are available. Such an application requires that models can make proper use of easily measured descriptors (e.g. physical or meteorological descriptors) to characterise catchment behaviour. One approach is to introduce catchment descriptors explicitly into distributed physically-based models, with parameters that can be directly measured in the field. These models can thus be used in theory (seldom in practice) without their parameters being calibrated against streamflow data. Conversely, parameters of lumped conceptual or empirical hydrological models that do not attempt to represent the physical complexity of the catchment, generally do not have any a priori physical meaning. The use of such models on ungauged catchments requires that links should be established between parameter values and catchment descriptors through regionalization studies.

An improved approach of parameter regionalization for lumped hydrological models is proposed. It intends to make a better use of the information contained in catchment descriptors to improve model performances. It differs in some ways from the classical approach based solely on a regression-like search of the link between model and catchment parameters. The methodology is applied to a parsimonious model on a large catchment sample.

2. CLASSICAL APPROACH IN REGIONALIZATION

The knowledge of streamflow characteristics on ungauged catchments is a major topic in operational hydrology. Indeed, in many projects of water engineering, there is no streamflow record available to determine regime characteristics. In these situations, alternative solutions must be found for the application of models whose parameters are usually calibrated against streamflow time-series. Two classical approaches can be distinguished:

- quantifying rainfall-runoff transformation at a regional scale, by describing similarities in the behaviour of (possibly neighbouring) catchments (see e.g. Nathan & McMahon, 1990; Burn & Boorman, 1993; Vandewiele & Elias, 1995);
- relating model parameters to catchment characteristics using regression-like methods.

This study focuses on the second approach, which is the one most commonly applied. It aims at relating two different hydrological characterisations of the basin. The first one is based on a physical description using attributes (soil, vegetation, geology, climate, etc.) thought to be relevant to the hydrological behaviour. The second one is based on modelling using parameters optimised for the study catchment. The way to relate both points of view is to establish a link between attributes and parameters. Many attempts were made with different models to establish satisfactory relationships (e.g., Servat & Dezetter, 1993; Johansson, 1994; Post & Jakeman, 1999; Seibert, 1999).

In most cases, the same methodology is followed:

- select a number of study catchments;
- calibrate the model on each catchment to obtain parameters characterising the basin;
- select a sample of physical (topography, physiography, land cover, pedology, geology...) or climatic variables which are thought to be relevant for the explanation of parameter values;
- establish relationships between model parameters and some of the pre-selected independent variables using simple or multiple regression;
- check the validity of these relationships by running the model with the calculated parameter values on catchments assumed to be ungauged.

Another original approach is to produce regional flow duration curves, followed by calibration of model parameters against these regional curves, as done by Yu & Yang (2000).

3. DESCRIPTION OF AN IMPROVED METHODOLOGY

The described methodology uses regression tools to derive predetermination equations after the model has been calibrated on all the study catchments. This is in fact a two-step method, which first characterises catchment behaviour with model parameters and then exploits the information contained in catchment descriptors to fit calibrated parameter values. One of the main problems associated with this method is that the derivation of regression equations does not directly account either for the way parameters act in the model (since the model does not play any role in the derivation process), or for the non-linearity and characteristics of the transformation performed by the model on rainfall inputs. All it does is to identify the best fit between model parameters and catchment characteristics. However since perfect fit is never achieved, and the model is non-linear, the identified linear regression equations do not give the best means of optimising model performances. This means that information in catchment variables can be used to explain parameter sample variance but not to explain the variance of streamflow time-series. However, researchers, and model end-users in practical applications, want to use the best (i.e., most reliable) modelled streamflow time-series on their ungauged catchment. Parameters are only an intermediate to this ultimate goal.

To give priority to model performances, it is proposed when deriving regression coefficients to choose these performances as objective functions rather than the error on parameters. To better illustrate the difference between the classical and the new approach, the following example of a simple interannual model is shown. It gives on catchment j ($1 \leq j \leq N$) mean annual streamflow Q_j as a function of observed mean annual rainfall P_j by:

$$Q_j = \frac{P_j^2}{P_j + A} + \varepsilon_j \tag{1}$$

where A is the single model parameter and ε_j is the error. On each catchment, an estimate of A is then given by:

$$\widetilde{A}_j = P_j . \left(\frac{P_j}{Q_j} - 1 \right) \tag{2}$$

In this simple case, an explicit expression of $\widetilde{A}_j$ is obtained. In the general case, $\widetilde{A}_j$ is estimated by a numerical optimisation procedure. Let's assume now that parameter A is linked to a catchment descriptor S by the following linear relationship:

$$A = \alpha . S + \eta \tag{3}$$

where α is a regression coefficient and η is model error. The value of α can be optimised by a least square regression algorithm, i.e. by minimising the following expression $OF1$:

$$OF1 = \sum_{j=1}^{N} \left(\widetilde{A}_j - \alpha . S_j \right)^2 \tag{4}$$

After combining Equations 2 and 4 and deriving the expression of $OF1$ as a function of α, one can obtain the optimal value $\widetilde{\alpha}$ of the regression parameter, which is given by:

$$\widetilde{\alpha} = \frac{\sum_{j=1}^{N} P_j . \left(\frac{P_j}{Q_j} - 1 \right)}{\sum_{j=1}^{N} S_j} \tag{5}$$

This is the value classically obtained in regionalization studies.

The second approach assumes the same type of relationship between A and S given in Equation 3. The objective is now to optimise model results (difference between observed streamflow and streamflow calculated with predetermined parameters), i.e. minimise the following function $OF2$:

$$OF2 = \sum_{j=1}^{N} \left(Q_j - \frac{P_j^2}{P_j + \alpha . S_j} \right)^2 \tag{6}$$

with the same notations as above. By deriving Equation 6 as a function of α, one obtains the following equation, which gives an implicit expression of :

$$\sum_{j=1}^{N} \frac{P_j^2 . Q_j}{\left(P_j + \widetilde{\alpha} . S_j \right)^2} = \sum_{j=1}^{N} \frac{P_j^4}{\left(P_j + \widetilde{\alpha} . S_j \right)^3} \tag{7}$$

Clearly the expressions of $\tilde{\alpha}$ given in Equation 5 is not a solution of Equation 7, what implies that the optimum value $\tilde{\alpha}$ for the regression equation is different from the one that minimises model error.

The first four steps of the classical methodology are used as a starting point in the proposed approach. The additional steps in the new methodology are:

- run the model on each catchment of the sample using parameter sets predetermined by regression equations and compute the value of the objective function based on all model performances to assess the worth of this regression equation set;
- for each parameter, select different regression equations with modified coefficients;
- test on each catchment all possible combinations of the previously selected equations. Calculate model performances in each case, then compute the objective function for each combination of equations. Keep the best solution, which is the new optimum if the objective function is better than that obtained at the previous iteration.

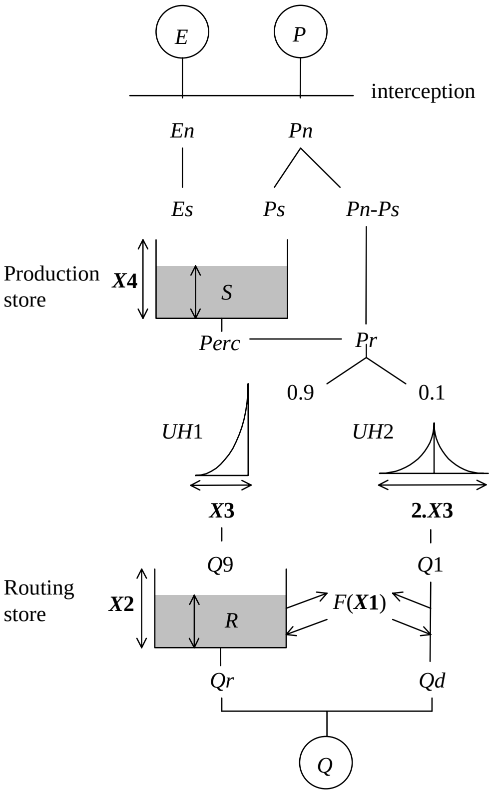
The last two steps are repeated until no further improvement can be achieved. The whole procedure could be automated using a numerical optimisation algorithm to calibrate regression coefficients. However when a large sample of catchments is used, this requires an excessive amount of computation. Note that if perfect fits in regression equations are found in the fourth step of the classical methodology, the proposed methodology coincides with the classical one. Of course such a case seldom, if ever, happens in practice.

The iterative nature of the method makes it quite tedious for models with a large number of parameters or when many variables describing catchment characteristics are used, which means that many regression coefficients are produced. If p is the number of model parameters and n_i the number of coefficients in regression equation for parameter i, then the procedure is similar to an optimisation problem in a space with $\sum n_{i(i \in <1,p>)}$ dimensions. It is more easily applied therefore in the case of parsimonious models and a low number of basin descriptors.

4. APPLICATION

As noticed by several authors (e.g. Post & Jakeman, 1999; Srikanthan & Goodspeed, 1988), the non-ambiguous determination of model parameter values is a prerequisite for a successful regionalization study. Indeed, overparameterised models generally do not have a unique set of parameters to fit observed streamflow values in the calibration period. The uncertainty in parameter determination then influences the reliability of regional predetermination equations. As a consequence, a parsimonious and reliable model must be used. Here the methodology is applied to a modified version of the daily GR3J model proposed by Edijatno *et al.* (1999). This four-parameter version (called here GR4J) was found to be more efficient on a large sample of catchments and was preferred to the GR3J model. Details of the model are given in Figure 1.

The GR4J model includes two water balance parameters (X1: water exchange coefficient; X4: capacity of production store) and two transfer parameters (X2: capacity of the non-linear routing store; X3: unit hydrograph time base). Several regionalization studies on previous model versions (Edijatno, 1991; Makhlouf, 1994) have shown that it is very difficult to find satisfactory regression equations for both water balance parameters. A solution is to use a monthly model with a similar structure, whose parameters can be more easily regionalized and linked to those of the daily model (Makhlouf, 1994). In this study, the simple solution of fixing these two water balance parameters to constant values (mean parameter values on the catchment sample) was adopted.



Interception (E : potential evapotranspiration; P : precipitation)

$if\ P \geq E, Pn = P - E,\ En = 0$

$else \quad Pn = 0, \quad En = E - P$

Production

$$Ps = \frac{Pn.\left(1-\left(\frac{S}{X4}\right)^2\right)}{1+\frac{Pn}{X4}.\left(1+\frac{S}{X4}\right)} \qquad Es = \frac{En.\frac{S}{X4}\left(2-\frac{S}{X4}\right)}{1+\frac{En}{X4}.\left(2-\frac{S}{X4}\right)} \qquad S = S + Ps - Es$$

Percolation

$$Perc = S - \left(S^{-4} + \left(\frac{9}{4}.X4\right)^{-4}\right)^{-\frac{1}{4}} \qquad S = S - Perc \qquad \Pr = Pn - Ps + Perc$$

Unit Hydrograph ordinates

$UH1(j) = SH1(j) - SH1(j-1)$

with $\quad 0 \leq j \leq X3,\ SH1(j) = \left(\frac{j}{X3}\right)^{\frac{5}{2}}$

$j > X3,\ SH1(j) = 1$

$UH2(j) = SH2(j) - SH2(j-1)$

with $\quad 0 \leq j \leq X3,\ SH2(j) = \frac{1}{2}\left(\frac{j}{X3}\right)^{\frac{5}{2}}$

$X3 < j \leq 2.X3, SH2(j) = 1 - \frac{1}{2}\left(2 - \frac{j}{X3}\right)^{\frac{5}{2}}$

$j > 2.X3,\ SH2(j) = 1$

Water exchanges

$$F = X1.\left(\frac{R}{X2}\right)^{\frac{7}{2}}$$

Direct flow component

$Qd = \max(0, Q1 + F)$

Non linear routing store

$$R = \max(\varepsilon, R + Q9 + F) \qquad Qr = R - \left(R^{-4} + X2^{-4}\right)^{-\frac{1}{4}} \qquad R = R - Qr$$

Total streamflow

$Q = Qr + Qd$

Figure 1: Schematic diagram and flow chart of the modified 4-parameter version of the GR3J model.

The studied catchments were chosen from the data sample used by Perrin *et al.* (2000), comprising 131 catchments on which the GR4J model performs satisfactorily. They are situated mainly in France (115) but also in the United States, Australia and Brazil and cover quite a wide range of climatic conditions. The catchment characteristics used to derive the regression equations consist of simple climatic variables. Model parameters were calibrated in each case on the longest available period of record. The Nash & Sutcliffe (1970) optimisation criterion, calculated on root square transformed streamflow, is used.

A limited set of basin descriptors was available in this study:

- catchment area SF [km²]
- mean annual rainfall PAM [mm]
- mean annual potential evapotranspiration EAM [mm]
- coefficient of rainfall seasonal irregularity CP [%], defined as:

$$CP = 100.\frac{P_{mx} - P_{mn}}{\overline{P_m}} \qquad (8)$$

where P_{mx} is mean rainfall of the wettest month, P_{mn} is mean rainfall of the driest month and $\overline{P_m}$ is mean monthly rainfall. This coefficient quantifies the variation of rainfall regime within the year. Transformations on parameters (mainly logarithmic) were carried out before regressions were established on catchment characteristics. The derived regression equations are given in Table 2. The corresponding determination coefficients R^2 for parameters X2 and X3 are 0.28 and 0.55 respectively. Solutions in Table 1 correspond to those obtained with the classical regionalization approach.

Table 1: Regression equation obtained for the GR4J model parameters on the sample of 131 catchments.

Parameter	X1 [mm d^{-1}]	X2 [mm]	X3 [d]	X4 [mm]
Regression equation	-0.62	$\frac{(CP.PAM)^{1.07}}{4866}$	$0.5+55.1\left(\frac{SF}{PAM^4}\right)^{0.16}$	415.7

Table 2: Regression equation obtained for the GR4J model parameters after coefficient adjustment on the sample of 131 catchments.

Parameter	X1 [mm d^{-1}]	X2 [mm]	X3 [d]	X4 [mm]
Regression equation	-0.40	$\frac{(CP.PAM)^{1.07}}{4866}$	$0.5+47.5\left(\frac{SF}{PAM^4}\right)^{0.16}$	535

Starting from those predetermination solutions, the proposed methodology was then applied. Constant values and regression coefficients were modified and new solutions were tested. The trial-and-error search was conducted to optimise model performances. The new predetermination solutions are given in Table 2.

The efficiency of the regression equations was quantified by using a numerical criterion based on percentiles of the distribution curves of results. Figure 2 illustrates model results obtained on the 131 catchments in the cases of calibrated parameters, classically regionalized parameters, parameters adjusted with the proposed methodology and mean parameters. It shows that only small improvements in model performances can be achieved by applying the proposed methodology. This means that the classical approach, although not optimal, seems to remain suitable for seeking predetermination equations.

It can also be noticed that using regionalized parameters is not much of an advantage over using mean values for all four parameters (X1 = -0.62 mm d^{-1}; X2 = 101.5 mm; X3 = 1.86 d; X4 = 415.7 mm). This situation can be linked to similar results obtained by Seibert (1999), which showed that the use of regionalized parameters on 11 basins in Central Sweden yield model performances only slightly better than taking the mean streamflow calculated on these eleven catchments.

5. CONCLUSION

A new methodology was tested to derive equations linking parameters of rainfall-runoff models and catchment characteristics for use on ungauged catchments. This methodology was thought to enable a better use of the information contained in basin descriptors for more reliable model performances. It was shown through a simple example that the classical regionalization approach based on the use of regression procedures on parameters alone cannot yield the theoretical optimum. The explicit use of model efficiency during the process of equation determination should yield more reliable performances.

However, in the simple illustrative case of the four-parameter lumped rainfall-runoff GR4J model, the improvement achieved is marginal in comparison with the results obtained by the classical regionalization approach. Furthermore, the use of mean parameters can give quite satisfactory results, not far from those based on regionalized parameters.

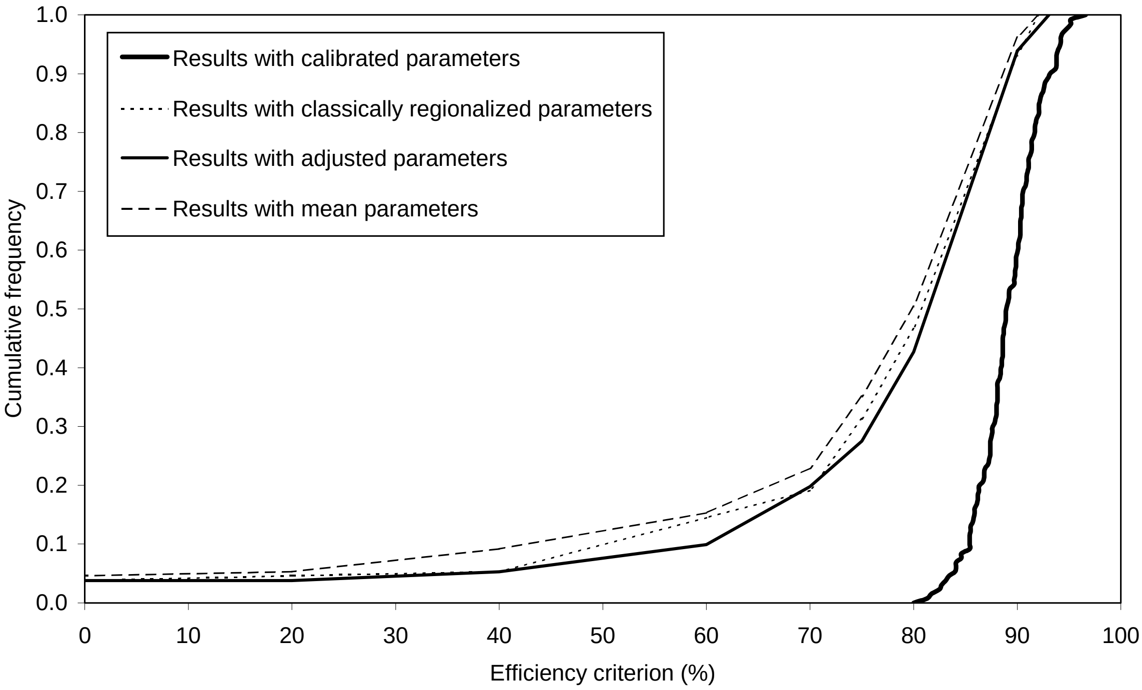


Figure 2: Distribution of results on the sample of 131 catchments using three different solutions of parameter determination.

ACKNOWLEDGEMENT

The authors wish to thank the anonymous reviewers for their suggestions to improve the text.

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Catchment hydrology and sustainable management (CHASM): generic experimental design

Quinn, P.F.[1], P.E. O'Connell[1], C.G. Kilsby[1], G. Parkin[1], J.C. Bathurst[1], P.L. Younger[1], S.P. Anderton[2] & M.S. Riley[3]

[1]*Water Resource Systems Research Laboratory, Department of Civil Engineering University of Newcastle upon Tyne, NE1 7RU, United Kingdom*
[2]*Department of Engineering, University of Durham, United Kingdom*
[3]*School of Earth Sciences, University of Birmingham, United Kingdom*

1. INTRODUCTION

CHASM is a new UK long term programme of research in which multi-scale catchment experiments, new theoretical developments and modelling will be used to generate the scientific understanding needed to underpin sustainable catchment management. The first major project to be funded under CHASM is NICHE (National Infrastructure for Catchment Hydrology Experiments) which will provide £4M of funding to instrument a set of seven UK mesoscale catchments; three of these are the focus of a NERC-funded Thematic Programme of Lowland Catchment Research (LOCAR), funded by the Natural Environment Research Council (NERC). Funding for NICHE, which commenced in January 2000, has been obtained from the UK Joint Infrastructure Fund through NERC. CHASM was conceived at the University of Newcastle; its conceptual basis and the generic experimental design proposed for the instrumentation of NICHE catchments are outlined in this paper.

2. KEY ISSUES AND ELEMENTS

The CHASM research programme will address the following key issues:

- The vast majority of catchment experiments have been conducted at the microscale (<10 km^2), only limited aspects of hydrological understanding can be transferred to larger scales (the scale issue).
- The range and intensity of anthropogenic influences within catchments is increasing and impacts are not fully understood, particularly in relation to ecological diversity and biogeochemical cycling.
- A better understanding is needed of how catchments are likely to behave under future climate conditions.
- Sustainable management plans for catchments need to be underpinned by good scientific understanding, particularly of the influences of abstractions on the hydrological and ecological regimes of catchments.

Key elements of CHASM include the following:

- a new focus on mesoscale (~100 km^2) catchment research to bridge the gap between the typical scale of past experimental catchment research (~10 km^2) and the catchment scales which are the focus of sustainable management issues;
- a major assault on the scaling issue, with new scaling theories to be developed and tested using multi-scale experiments;
- a set of n mesoscale nested catchment experiments which
  - sample heterogeneity in rainfall/topography/soils/vegetation/geology comprehensively
  - cover a range of anthropogenic impacts;
- a scientific platform for new developments in hydro-ecological research;
- an integrated monitoring and modelling approach in which modelling is used from the outset to design the catchment experiments and to steer field campaigns.

3. GENERIC EXPERIMENTAL DESIGN

A key set of elements has been chosen as the basis of the Generic Experimental Design.

- landscape classification;
- an adaptive, staged approach to instrumentation:
  - Mobile Instrumentation
  - Permanent Instrumentation
  - Staged Instrumentation
- a multi-scale approach with a nested structure;
- understanding and resolution of heterogeneity (through integrated monitoring and modelling);
- reclassification of the landscape, and a repeat of the cycle.

The experimental design is seen as an iterative process in which the effects on catchment response of heterogeneity in topography, soils, vegetation and geology are understood and resolved, leading ultimately to the classification of the landscape into hydrologically homogeneous domains.

4. LANDSCAPE CLASSIFICATION

It is envisaged that digital maps of topography, soils, vegetation and geology will, in the first instance, be used together with a priori knowledge and understanding of the dominant controls on hydrological response to produce a first attempt at landscape classification. It is recognized that any classification scheme must reflect a specific purpose, which, in the case of catchments, can be defined in terms of hydrological, geomorphological or ecological response. The Permanent, Staged and Mobile Instrumentation will be deployed in accordance with this initial classification. As data become available and models are developed, the under-standing of the controls on hydrological response will be enhanced, leading to the re-classification of the landscape and the redeployment of instrumentation to sample unresolved hydrological variability.

5. MOBILE INSTRUMENTATION - THE GREEN MACHINE

'The Green Machine' (see Figure 1) is an all-terrain vehicle that will be adapted to carry out rapid surveys in the field. The Green Machine is to be fitted with a high resolution, real time, Global Positioning System and a set of geophysical surveying equipment (including a ground conductivity meter and a seismic refraction kit). A number of geophysical experiments are envisaged that will work in tandem with the staged and permanent instrumentation. The Green Machine will be used in the initial land classification scheme to survey prospective instrumentation sites to guarantee that those sites meet with the generic experimental design criteria of the CHASM project. The vehicle will also be used for the installation of field equipment (that includes a drilling rig) and for downloading data loggers directly onto an on-board computer.

Figure 1: The Green Machine for rapid surveys in real time, with accurate mapping and navigation capability. It is a lightweight all-terrain vehicle fitted with a drilling rig, GPS and geophysical equipment.

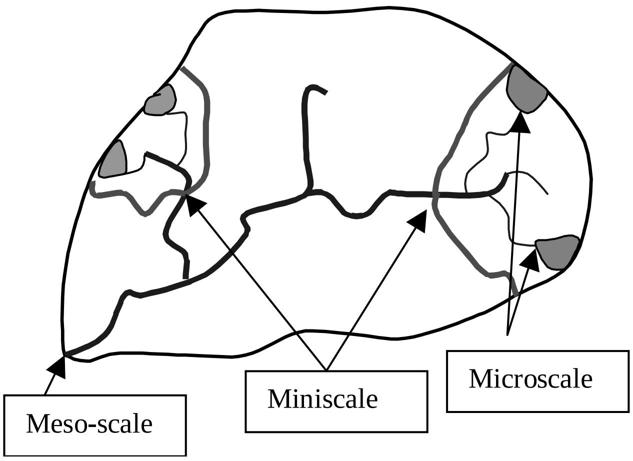

Figure 2: Permanent instrumentation and a multi-scale approach with nested structure, including river gauging stations with nested structure, observation boreholes and river aquifer experiments, hydrometeorological stations and rain gauges, hillslope instrumentation (runoff troughs, lysimeters) and suspended sediment and water quality monitors.

6. PERMANENT INSTRUMENTATION AND A MULTI-SCALE APPROACH WITH A NESTED STRUCTURE

Permanent instrumentation will be positioned within each catchment to follow a multi-scale nested structure consisting of microscale (1 km^2) and miniscale (10 km^2) catchments (see Figure 2). A major objective of CHASM is to scale-up process representation and catchment variability to the mesoscale (100-200 km^2). Miniscale catchments are seen as a key scale for observing the effect of local variability but also for studying mixing and attenuation processes. The microscale catchments will help to resolve spatial variability in responses, by monitoring processes within distinct land units as defined from the basic landscape classification scheme.

7. STAGED INSTRUMENTATION

Initially a series of detailed point scale measurements will be made within the microscale catchments (see Figure 3). A dense network of logged instrumentation will generate the basic data needed to establish the mean and distribution of key hydrological variables, such as the water table dynamics, the soil moisture regime and the evaporative dynamics, for a patch of land approximately 50m * 50m in extent. Patch instrumentation will improve the representation of catchment variability by targeting the heterogeneity seen at the hillslope scale. Two to three patches will be implemented on hillslopes within a microscale catchment to capture this heterogeneity. As this will require a large number of instruments, a staged instrumentation approach has been designed. Firstly, a full set of instruments are installed, which are left to record data whilst other patches are implemented. The data from the instruments will be analyzed frequently, until it is agreed that the mean hydrological behaviour of the patch has been established. At this stage, several instruments that represent the mean behaviour of the patch will be left in situ, but the remaining instruments are removed and used in new patches. This process will allow the first goal of establishing patches in all microcatchments to be fulfilled, but also offers the opportunity for other patches to be set up elsewhere in the mini- or mesoscale catchments.

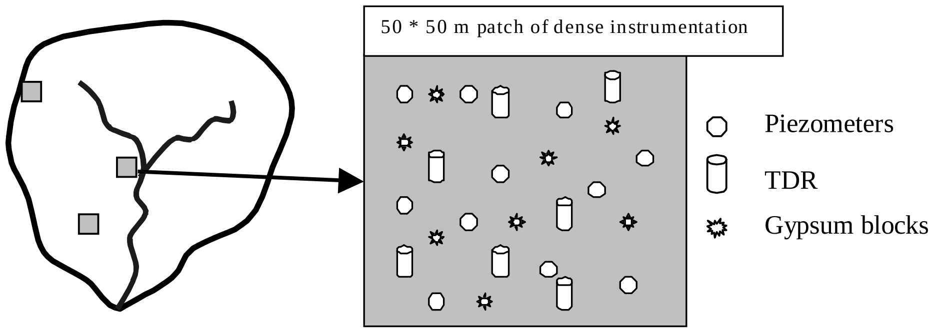

Figure 3: Staged instrumentation within a microscale catchment and the use of patches to capture hillslope scale variability.

8. THE NICHE CATCHMENTS

The NICHE project is being implemented by two consortia (Table 1 and Figure 4). The NICHE-CHASM consortium will focus on four predominantly upland catchments (Oona, Feshie, Eden and Upper Severn) while the NICHE-LOCAR consortium will focus on three lowland catchments which overly major UK aquifers (Tern, Pang/Lambourn and Frome/Piddle). It is intended that the Generic Experimental Design should, as far as possible, be implemented across all seven catchments. NICHE task forces have now been set up by both consortia to develop specific experimental designs for implementation on the two groups of catchments, and to ensure that the designs for individual catchments conform as far as possible with the Generic Experimental Design.

Table 1: Partner organizations.

NICHE Project	
NICHE-CHASM	**NICHE-LOCAR**
University Of Newcastle	Imperial College London
University Of Aberdeen	University of Birmingham
University Of Dundee	University of Exeter
University Of Durham	NERC British Geological Survey
University Of Lancaster	NERC Centre for Hydrology and Ecology
University Of Leeds	• CEH Wallingford (Hydrology)
University Of Ulster	• CEH Dorset (Freshwater Ecology)
NERC Centre for Hydrology and Ecology	
• CEH Wallingford (Hydrology)	
• CEH Dorset (Freshwater Ecology)	

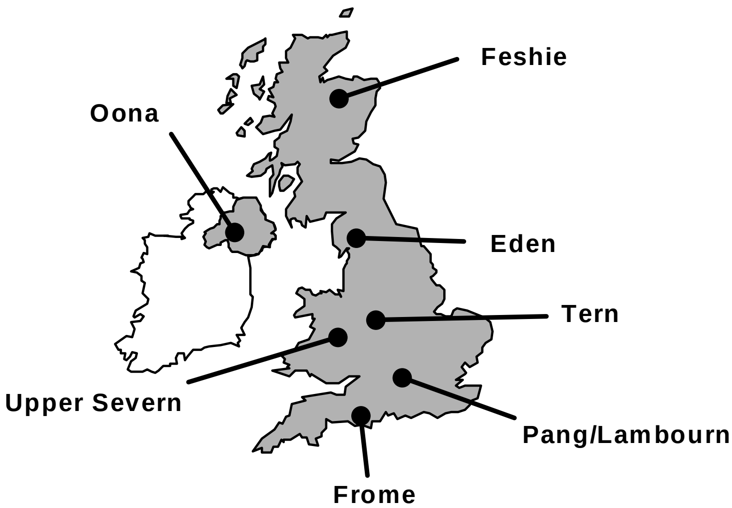

Figure 4: Locations of the selected catchments.

Monitoring and modelling water quantity and quality in a pilot catchment in North-western Spain

Soriano, G. & J. Samper

E.T.S. Ingenieros de Caminos, Canales y Puertos, Universidad de La Coruña, Campus de Elviña, s/n, 15192 La Coruña, Spain
Email: soriano@iccp.udc.es

ABSTRACT

Groundwater has been used extensively in the past as a reliable source for water supply in medium-sized and small villages in Galicia, a region located in north-western Spain. Most water wells and springs are located in poorly understood shallow aquifers in crystalline and metamorphic rocks. The lack of appropriate hydrogeological studies, and groundwater contamination by farming and agricultural activities, have led to a progressive abandonment of groundwater in favour of large surface water projects, constructed with public funding, and usually on a political basis. In order to bridge the gap in the knowledge of the hydrology and geohydrology of the area, a small drainage basin near La Coruña has been intensively studied. Here we report the main results achieved so far on monitoring and modelling water quantity and quality in this area. Conclusions can be extended to other catchments of the north-western corner of the Iberian Peninsula.

1. INTRODUCTION

Galicia is a region located in north-western Spain. Its population is mainly rural and much dispersed. Groundwater has been used extensively in the past as a reliable source for water supply in medium-sized and small villages. The lack of appropriate hydrogeological studies and groundwater contamination by farming and agricultural activities, have led to a progressive abandonment of groundwater. In order to bridge the gap on the knowledge of the hydrology and geohydrology of the area, the Valiñas basin has been studied since 1995, and has been instrumented since 1997. The catchment (see Figure 1) is near the city of La Coruña, bounded by the Zapateira mountains to the north, the Bregua and Santa Leocadia mountains to the west and by the Xalo mountain to the south, which has an altitude of more than 500 m a.m.s.l. The outlet to Mero River is located to the north-east, at 10 m a.m.s.l. The surface area of the catchment is 36.3 km^2 and its main course is 12 km long. The basin is mostly located on granitic rocks.

2. MONITORING WATER QUANTITY AND QUALITY

Hydrogeological studies in the Valiñas catchment began on December 1995, and since October 1997 a number of control points have been monitored. The location of these points is shown in Figure 1. Data collected from December 1995 include the following (see Figure 2):

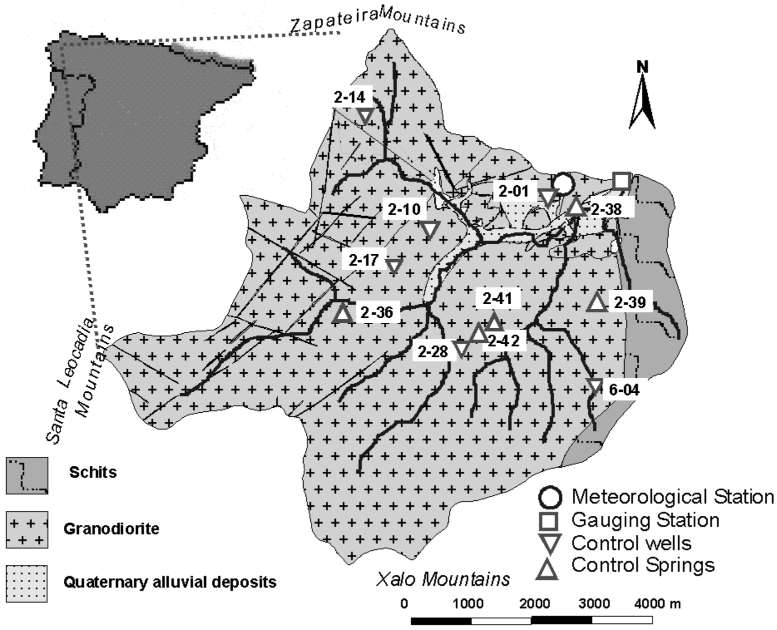

Figure 1: Location of Valiñas drainage Basin, geological frame and positions of the control points.

- *River gauging*. The gauging station is a natural section of Valiñas River, under a bridge. Periodic direct gauging of the water current (obtained by using a velocity profile method) was performed since December 1995, to get the discharge-rating curve. This curve has been reported to vary with canal changes, so it has had to be recalibrated periodically. Automatic recording of the water level in the gauging station has been made since October 1997 by an ultrasonic sensor coupled to a data logger.
- *Inventory of water points*. A database was prepared containing 74 water points in the basin. The data include: 18 public springs, 14 drilled wells, 37 dug wells and 5 boreholes drilled for research purposes. Eight sampling campaigns were performed so as to determine the water level in wells and to carry out the gauging of the springs, in order to obtain piezometric maps. Six wells and five springs have been checked twice a month since October 1997. A pressure transducer installed in one of the monitoring wells provided a continuous record of the water table fluctuations.
- *Meteorological recording.* An automatic meteorological station was installed in October 1997; this records air temperature, rainfall intensity and wind direction and speed. In addition, several rain gauges were located at different heights within the basin. Data from three more meteorological stations belonging to the National Meteorological Service show a good correlation with the data measured in the Valiñas station (see Figure 2, showing the rain rates in Alvedro and Valiñas stations).
- *Sampling campaigns*. Two hydrochemical, microbiological and isotopic sampling campaigns were carried out.

3. HYDROGEOLOGICAL CONCEPTUAL MODEL

The hydrogeological data obtained indicate the existence of two subsurface flow systems in the Valiñas basin. A shallow aquifer of 10 to 20 m depth contains a rather porous medium developed within the granite alteration zone. Underlying this aquifer, a less permeable aquitard is found in the fractured granite, where water flows mostly through fractures. Most avail-able data come from the shallow aquifer where the phreatic surface reproduces in a smooth manner the shape of the topographic surface (see Figure 3).

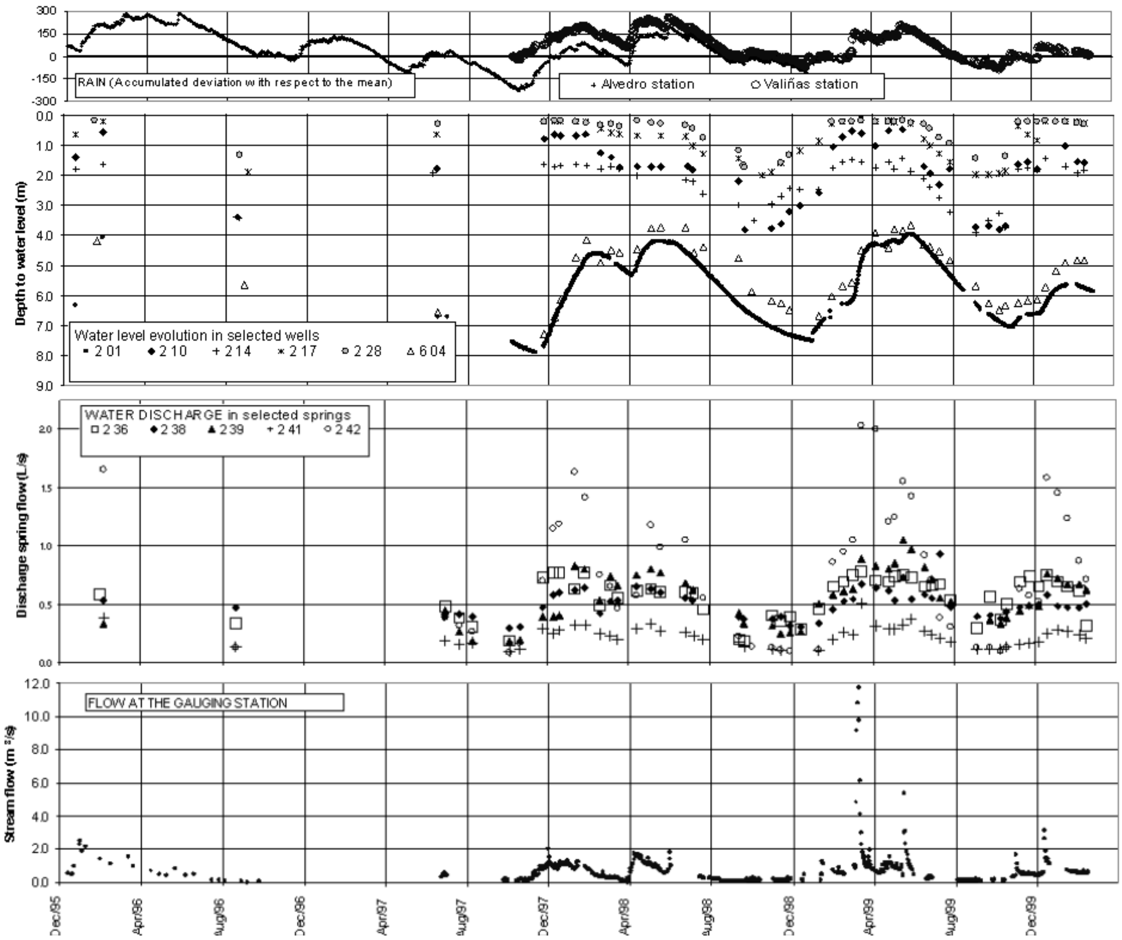

Figure 2: Recorded data in Valiñas Basin: cumulative rainfall deviation (top), water level depth, spring flows and streamflow rates (bottom).

Pumping tests performed on shallow boreholes attest a large spatial heterogeneity in hydraulic conductivity. Figure 4 shows an example of a test carried out in a group of bore-holes drilled for research purposes. These boreholes have a depth of 16 m, and the distance between them is just a few meters. The one labelled VALP1 was pumped, while drawdown was measured in four others. Interpretation of the tests was performed with the code INT-PULSO (Juncosa *et al.,* 1996). As can be seen in Figure 4, the model gives a good fit for measured data in VALP1 and VALP2 with a transmissivity of 15 $m^2\ d^{-1}$, but it is impossible to reconcile the minimal drawdown measured in VALP3 and VALP4 with this transmissivity value. For another pumping test between these boreholes, 0.5 $m^2\ d^{-1}$has been calculated for transmissivity.

The heterogeneity in the aquifer can also be observed in the water level and spring flow records (see Figure 2) which very often show smooth rising and falling patterns in re-sponse to wet and dry periods. Two different kinds of response can be distinguished. Bore-holes featuring a deep water level, and some of the springs, show a bigger annual oscillation (4 m and 2 $l\ s^{-1}$, respectively), while these oscillations are much lower (1.5 m and 0.25 $l\ s^{-1}$) in shallow water levelled wells and springs with lower mean flow rate. In this second group, the response to wet periods is almost instantaneous, and levels rise to a value that marks a maximum recharge level (rooted zone in the soil). These differences are not only due to the heterogeneity in the aquifer, but also to the fact that deeper zones of the aquifer show semi-confining conditions (the lower storage coefficient allows more pronounced oscillations).

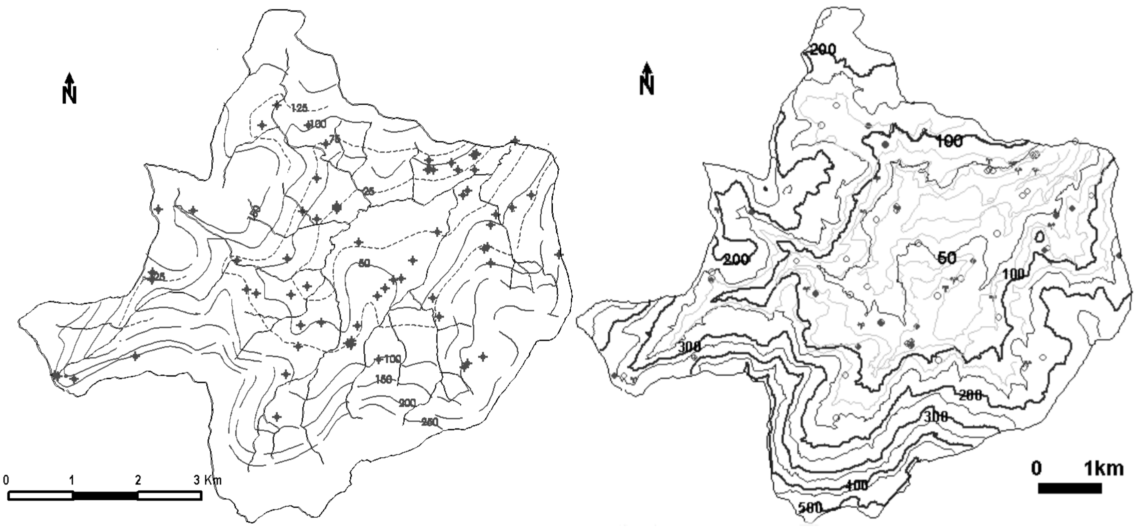

Figure 3: Mean piezometric surface (left) and topographic surface (right).

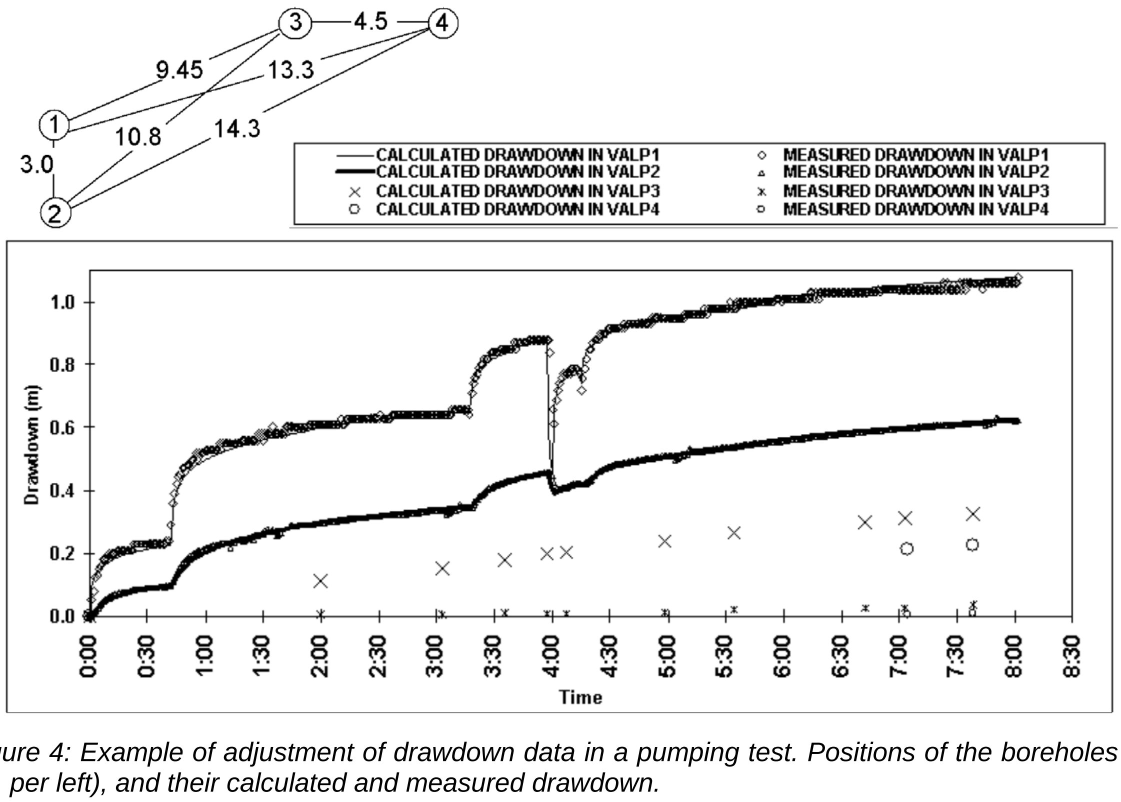

Figure 4: Example of adjustment of drawdown data in a pumping test. Positions of the boreholes (upper left), and their calculated and measured drawdown.

4. HYDROCHEMICAL AND POLLUTION DATA

Groundwater in the Valiñas basin usually shows a slow mineralization, resulting in low values for the Electrical Conductivity (EC). The mean value of EC is 280 µS cm^{-1}, corresponding to low solubility silicated rocks and a short residence time of the water in the aquifer.

Although water composition is quite homogeneous in the aquifer, some hydrochemical groups can be distinguished (see Figure 5); most of the waters are dominated by sodium-chloride or calcium-bicarbonate, but there is a number of them that are characterised by sodium-magnesium-chloride or by sodium-bicarbonate.

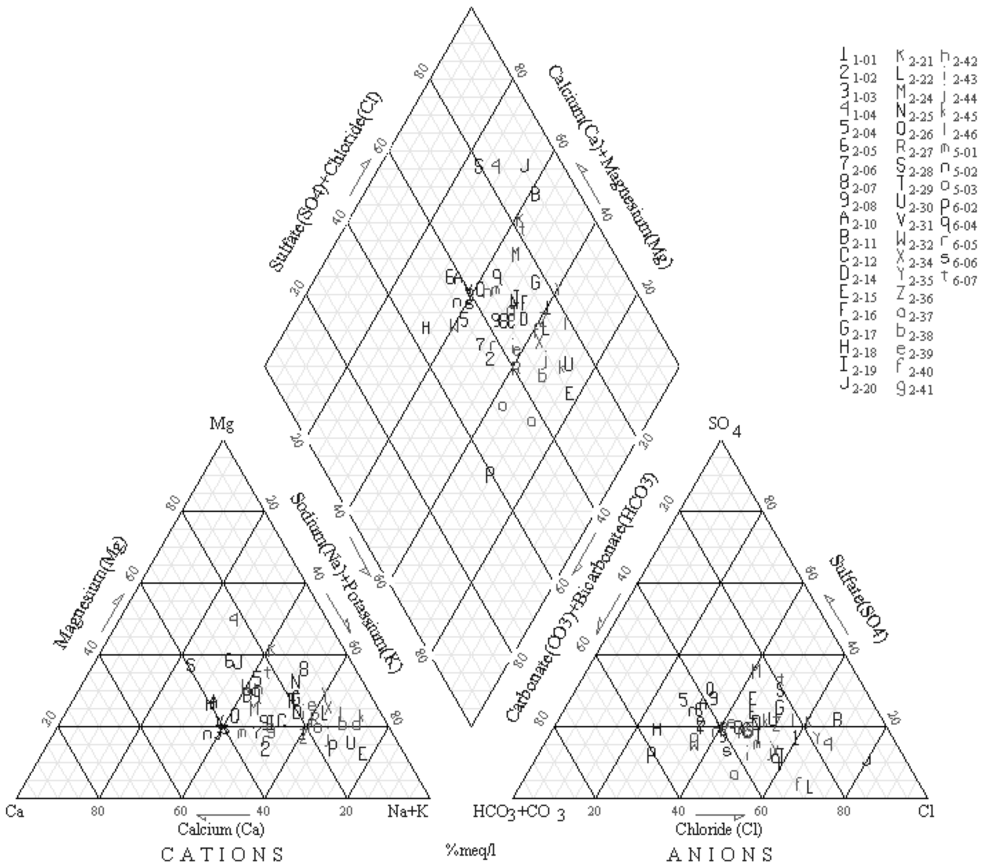

Figure 5: Piper diagram of groundwater collected in September 1996.

A very good correlation can be found between EC and land use. The two maps in Figure 6 represent land uses (left) and EC for the 1996 campaign (notice that the land use map is a bit distorted because it is based on an aerial photography). The coincidences between land crops areas and zones featuring high values of EC can be clearly observed. As a consequence, the chemical composition of waters is assumed to be affected by antropic activity. In fact, high nitrate concentrations were found in all the sampling campaigns (Soriano & Samper, 1997; Molinero *et al.*, 1999) and were taken as an indication of groundwater contamination. Data from a second chemical campaign, in which microbiological analyses were performed at 57 points (including wells and springs), indicated that only one of the samples fitted the portability criteria. The presence of faecal coliforms and faecal enterococci was detected in most of the groundwater sampling points, demonstrating the existence of a severe contamination of faecal origin.

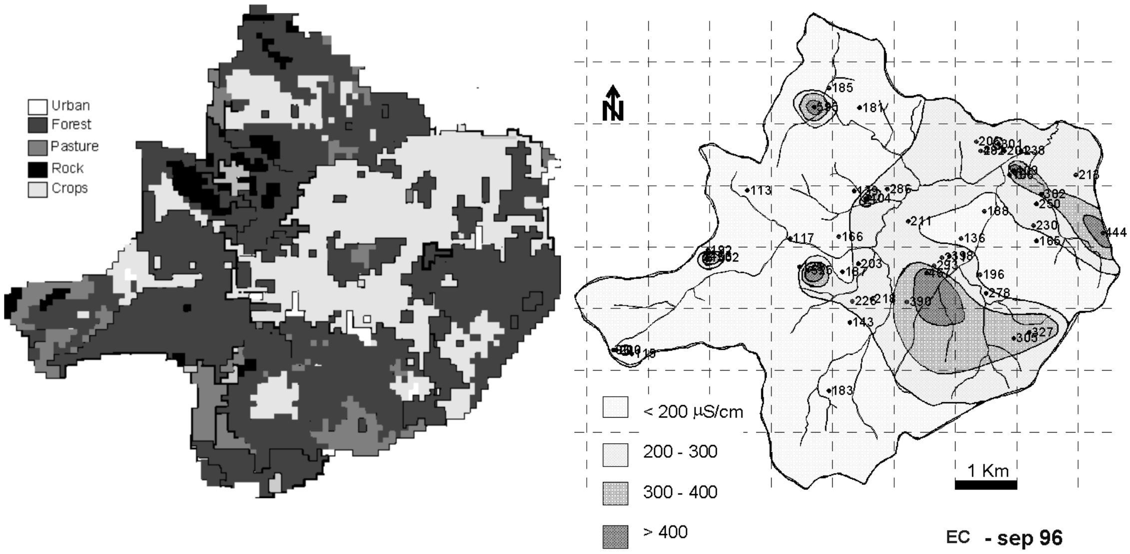

Figure 6: Land use map (left) and EC in groundwater in September 1996 (right).

Multivariate statistical correspondence analyses of hydrochemical and microbiological data, point out a clear relationship between high concentrations of faecal coliforms and enterococci and the depth of the water table, indicating that areas with a shallow water table are more vulnerable to pollution. There seems to be a close relation between the appearance of nitrates and the hydrogeochemical composition of the water (the calcium-magnesium-chloride waters always have high nitrate concentrations).

Table 1: Results of the daily hydro-meteorological balance.

Parameter	**Mean annual value [mm]**
Rainfall	1129.2
Interception	114.2
ETP	731.2
ETR	539.6
Recharge	76.7
Surface runoff	10.8
Interflow	361.9
Total discharge	604.37

5. MODELLING WATER QUANTITY

A lumped daily hydro-meteorological balance model was performed using the user friendly code VISUAL-BALAN (Samper *et al.,* 1999). Preliminary results for the balance were presented in Samper *et al.* (1997) and Soriano & Samper (2000). Data from three meteorological stations have been used as input data in the balance; the Valiñas station is considered to be the main one, but when no data are available for a particular day, the code allows for the infill of the series using data from other sites. The balance has been performed from October 1994 to September 1999. The evolution in the groundwater head in point number 1-02 and the discharge rate at the gauging station, measured since December 1995, have been used to calibrate the model.

The results of this model perfectly match the water head data as well as the total discharge data measured at the gauging station (see Figure 7). The values of the mean annual components of the water budget are listed in Table 1. The largest component of the budget corresponds to the subsurface runoff. The mean annual value for recharge calculated in the balance period, was 76.7 mm, and represents almost 15% of the total rainfall.

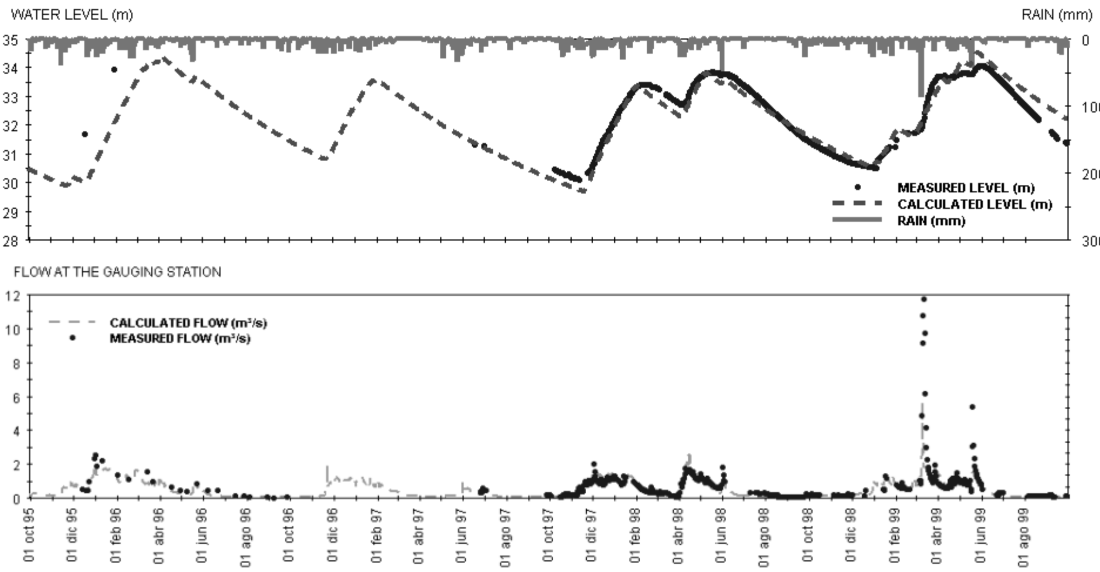

Figure 7: Level and streamflow adjustment obtained with the hydro-meteorological balance. Computed (dash lines) and measured (symbols) groundwater levels and stream flows.

6. CONCLUSIONS

Groundwater plays a strategic role in the Valiñas basin. Its 5,000 inhabitants rely on the groundwater obtained from springs, from wells tapping the shallow weathered granite zone, and from deep wells drilled in fractured granite. The population is largely dispersed around the basin, making it extremely difficult to construct public sewage systems. Most houses therefore make use of poorly-designed and badly-operated septic tanks. These, together with the high density of small cattle farms all throughout the basin with no waste treatment, and the abuse of organic fertilizers in the area, have been the cause of extensive pollution of the groundwater. In some of the cases pollutants find their way directly into groundwater because of poor well design; moreover some wells have no sealing at all. Adequate planning for fertilizer application, correct cattle waste processing and suitable design and location of septic systems is definitely needed in order to prevent groundwater contamination.

Future works in the catchment will focus on:

- the evaluation of water resources - the hydro-meteorological water balance needs to be tested against hydrochemical data.
- the identification of contamination sources.

Several isotopic and chemical methods, such as nitrogen and boron isotopes, and Cl/Br ratio, are being considered in order to discriminate groundwater contamination sources.

ACKNOWLEDGMENT

Funding for this work was provided by Research Projects of the Spanish Ministry of Education (Grant AMB95-0997-C02-01) and the Department of Education of the Autonomous Government of Galicia (XUGA94a1180). The first author benefited also from a scholarship paid by the Ministry of Education (FPI Program).

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Investigation of chaotic behaviour in precipitation and temperature series with high time resolution

Stehlík, J.

Czech Hydrometeorological Institute, Department of Experimental Hydrology
Na Sabatce 17, 143 06 Praha 4, Czech Republic
Email: stehlik@chmi.cz.

ABSTRACT

The purpose of this contribution is to try to detect deterministic chaos in precipitation and temperature series with high time resolution in order to investigate their chaotic behaviour, and to determine their predictability horizon. For detecting the deterministic chaos the Lyapunov exponent method is used. Average mutual information is computed to determine a non-linear correlation time for both series. Degrees of freedom operating in the observed data are determined by means of the false nearest neighbours' method. Nine degrees of freedom were found to govern the dynamics of the precipitation series, and 5 that of temperature. Local and global Lyapunov exponents have been computed. The highly intermittent nature of the rainfall causes problems with the interpretation of the Lyapunov exponents for the precipitation series, although realistic results have been obtained for the temperature series. The maximum Lyapunov exponent is larger than zero, thus proving the chaotic dynamics of the system and the sensitivity of dependence on initial conditions. A predictability horizon has been computed for the temperature series.

1. INTRODUCTION

Hydrologically, precipitation and temperature are undoubtedly important variables. Precipitation is the driving force of the hydrologic system. Temperature influences evapotranspiration and the precipitation phase (rain, snow) and therefore plays an important role in the water balance. Precipitation is characterized by high spatial and temporal variability. Owing to the highly non-linear relationships governing the rainfall dynamics, long term forecasting can only be done in a stochastic way. This makes long term, deterministic forecasting impossible.

The purpose of this contribution is to try to detect deterministic chaos in precipitation and temperature series with high time resolution in order to investigate their chaotic behaviour, and to determine their predictability horizon. The data used have been taken from a climatic station located in the Jizerka experimental basin, on the top of the Jizera Mts. in the northern part of the Czech Republic.

A chaotic system is defined as a deterministic system in which small changes in the initial conditions may lead to completely different behaviour in the future. The signal from the chaotic system is often, at first sight, indistinguishable from a random process, despite being driven by deterministic dynamics.

To date, a lot of attention has been devoted to analyzing various natural processes and elements by means of deterministic chaos approach e.g. Kurths & Herzel (1987), Henderson & Wells (1988), Rodriguez-Iturbe *et al.* (1989), Sharifi *et al*. (1990), Jayawardena & Lai (1994), Palmer *et al.* (1996), Sivakumar *et al.* (1998) and Stehlík (1999).

2. METHODS

The theory of deterministic chaos has enabled the development of new methods for analyzing the observed time series. In this study the Lyapunov exponent method (Wolf *et al*., 1985) is used.

2.1. Phase space

The time series is assumed to be generated by a non-linear dynamic system with *D* degrees of freedom. It is therefore necessary to construct an appropriate series of state vectors $X^D(t)$ with delay coordinates in the *D*-dimensional phase space:

$$X^D(t) = \left[X(t), X(t+\tau),\ldots, X\left(t+(D-1)\tau\right)\right] \tag{1}$$

where τ is an appropriate time delay. The trajectory in the phase space is defined as a sequence of *D* dimensional vectors. If the dynamics of the system can be reduced to a set of deterministic laws, the trajectories of the system converge towards the subset of the phase space, called the attractor.

The time delay τ can be defined by means of an autocorrelation function or, as used in this study, the average mutual information method (Fraser & Swinney, 1986). This method defines how the measurements $X(t)$ at time *t* are connected in an information theoretic fashion to measurements $X(t+\tau)$ at time $t+\tau$ (Abarbanel, 1996). The average mutual information is defined as:

$$I(\tau) = \sum_{X(i),X(i+\tau)} P\left(X(i), X(i+\tau)\right)\log_2\left[\frac{P\left(X(i), X(i+\tau)\right)}{P\left(X(i)\right)P\left(X(i+\tau)\right)}\right] \tag{2}$$

where *i* is total number of samples. $P\left(X(i)\right)$ and $P\left(X(i+\tau)\right)$ are individual probabilities for the measurements of $X(i)$ and $X(i+\tau)$. $P\left(X(i), X(i+\tau)\right)$ is the joint probability density for measurements $P\left(X(i)\right)$ and $P\left(X(i+\tau)\right)$. The appropriate time delay τ is defined as the first minimum of the average mutual information $I(\tau)$. Then the values of $X(i)$ and $X(i+\tau)$ are independent enough of each other to be useful as coordinates in a time delay vector, but not so independent as to have no connection with each other at all.

2.2. Lyapunov exponents

Lyapunov exponents are long term average exponential rates of divergence or convergence of nearby states in the phase space. If a system has at least one positive Lyapunov exponent, then it is assumed to be chaotic. There are as many Lyapunov exponents as there are degrees of freedom in the system. According to Abarbanel (1996) the local and global Lyapunov exponents can be distinguished.

Local Lyapunov exponents $\lambda_i\left(X^D(t),L\right), i=1,D$ depend on the point on the attractor $X^D(t)$ where the perturbation is initiated and the number of time steps *L*. When *L* approaches infinity (or in practice becomes large enough) these exponents become independent of $X^D(t)$. Average local Lyapunov exponents are obtained by averaging over the state space variable $X^D(t)$. This average local Lyapunov exponent converges as a power of *L* to the global Lyapunov exponent and does not depend on the initial conditions of the orbit.

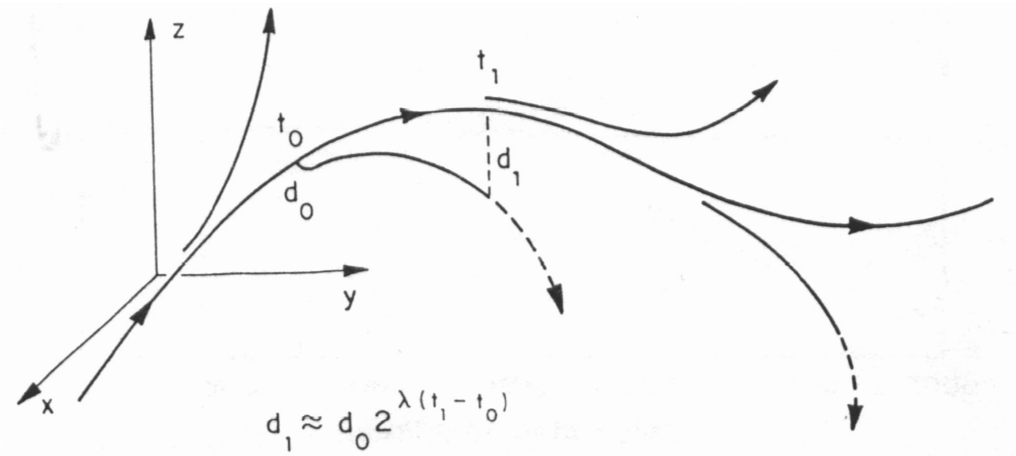

Figure 1: Evaluation of the largest Lyapunov exponent (Moon, 1987).

First algorithms for Lyapunov exponents’ estimation have been presented by Wolf *et al.* (1985). To measure the divergence of orbits it is necessary to average the exponential growth at many points along the trajectory (Figure 1). Considering two points that are close in state space at time t_{k-1} having the distance $d_0\left(t_{k-1}\right)$, their distance at time t_k is the original distance multiplied by $2*\exp\left(\lambda\left(t_k-t_{k-1}\right)\right)$. When the new distance becomes too large departing from the exponential behaviour, one looks for a new nearby trajectory (Rodriguez-Iturbe *et al*., 1989). The largest global Lyapunov exponent (λ_1) determines the average horizon of global predictability for the system. It is defined as:

$$\lambda_1=\frac{1}{t_M-t_0}\sum_{k=1}^{M}\log_2\frac{d\left(t_k\right)}{d_0\left(t_{k-1}\right)} \tag{3}$$

where *M* is the number of replacement steps, $d_0\left(t_{k-1}\right)$ is the Euclidean distance between the point $\left\{X\left(t_{k-1}\right),X\left(t_{k-1-\tau}\right),X\left(t_{k-1-2\tau}\right),...,X\left(t_{k-1-(D-1)\tau}\right)\right\}$ and its nearest neighbour, and $d\left(t_k\right)$ is the evolved length of $d_0\left(t_{k-1}\right)$ at time t_k.

Before computing the largest Lyapunov exponent, the dimension *D* of the phase space has to be determined. In this study the dimension was computed using the false nearest neighbours’ method. This enables the determination of the dimension in which the attractor is unfolded (Kennel *et al*., 1992).

3. RESULTS AND DISCUSSION

Precipitation and temperature data from the Jizerka climatic station, measured in 30 minute time steps, have been analyzed. The precipitation series contains 7500 points: 28 May - 31 October 1997, and the temperature series has 17520 points: 1 November 1996 - 31 October 1997.

The results are summarized in Table 1. By means of the average mutual information method, the time delay τ was determined. It is six times higher than the sampling interval for the precipitation (180 min), and seventeen times higher than that for temperature (510 min).

The dynamic model needed to describe the data has 9 dimensions for precipitation and 5 for temperature. This indicates the presence of more degrees of freedom in the system governing the precipitation series, than in that governing temperature series.

Table 1: Time lag τ, phase space dimension d and global Lyapunov exponents λ_i for precipitation and temperature time series.

Variable	$\tau[\text{min}]$	***d***	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7	λ_8	λ_9
Precipitation	180	9	-	5.76	3.94	2.49	1.24	2.11	1.53	0.15	-0.63
Temperature	510	5	0.62	0.42	0.21	-0.08	-0.76	-	-	-	-

The first global Lyapunov exponent for precipitation data is not available, as its computation is mathematically not defined. In addition to this, the sum of the remaining 8 exponents is unrealistically high (16.59). However this sum should be negative as required for a realistic dissipative system. These problems could be due to a large number of zeros (intervals with no precipitation) in the series. High intermittence of rainfall occurrence led to 6636 zeros (88 % of data). As mentioned by Sivakumar (2000), this is a common problem in hydrological applications of chaos theory.

For temperature series all Lyapunov exponents are defined. Average local Lyapunov exponents for different numbers of steps are displayed in Figure 2. For a large number of steps the approach of the local Lyapunov exponents to their constant global values is evident. Global Lyapunov exponents are shown in Table 1. The largest global exponent is greater than zero. The deterministic chaos in the temperature series is therefore proven. Two exponents are negative. The sum is larger than zero, however not as distinctly as in the case of precipitation. An interpretation of the results has therefore been allowed. The largest global Lyapunov exponent λ_1 equals 0.62, so it is possible to predict the dynamics forward in time about

$$\frac{T_s}{\lambda_1} = 48\,\text{min}$$

where $T_s = 30\,\text{min}$ (the sampling interval). None of the exponents is zero which would indicate that the underlying dynamics comes from a system of differential equations. However, even in the case where the equations are known, the predictions could not be better than the predictability horizon computed above.

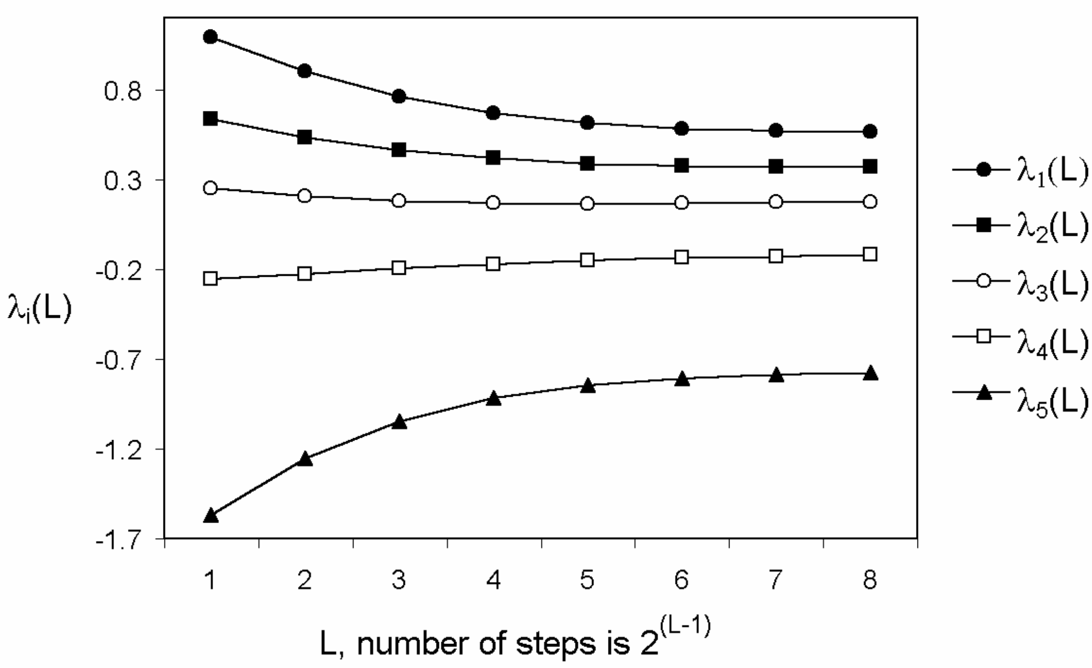

Figure 2: The average local Lyapunov exponents for temperature series.

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Monitoring and statistical modelling of the surface and subsurface flow at different scales

Talamba, D.[1], C. Joerin[1], A. Musy[1] & I. Balin[2]

[1] Institute of Soil and Water Management (IATE/HYDRAM), DGR, EPFL
1015, Lausanne, Switzerland
Email: daniela.talamba@epfl.ch, christophe.joerin@epfl.ch, andre.musy@ epfl.ch
[2] Laboratory of Air and Soil Pollution (LPAS), DGR, EPFL
1015, Lausanne, Switzerland
Email: jean.balin@epfl.ch

ABSTRACT

The aim of this paper is to present flow monitoring techniques used to study the hydrological processes at different scales. Environmental tracing on the Haute Mentue catchment has permitted the study of hydrological processes at the catchment scale. The results obtained cannot be transferred to a local scale. Statistical models with both quantitative and qualitative variables have been used and their results give evidence of the importance of the basin physical properties in explaining the spatial variability of hydrological response. In order to study hydrological processes at the hillslope scale, a dye tracing experiment has been carried out on the same catchment. The results confirmed those of the environmental tracing but they can’t be extrapolated to a global scale or to other kinds of contributing area. The dye tracing is complementary to the environmental tracing, and their association may be a promising line of study to take in identifying and quantifying hydrological processes.

1. INTRODUCTION

This work was done within the framework of the research at the IATE/HYDRAM Institute in order to facilitate the study of hydrological processes at different scales. The study area is the Haute-Mentue experimental catchment, situated in the west of Switzerland (Figure 1).

The Haute-Mentue forms the upper part of the Mentue River, which is a tributary of the Neuchatel Lake. The environmental tracing represents an integrating technique, which can contribute to the understanding of the hydrological processes at the catchment scale. In an attempt to understand the hydrological processes that occur at the local scale, dye tracers have been used to monitor the subsurface flow. In order to account for the spatial variability of the hydrological response at a regional scale, statistical modelling was carried out using physical parameters such as rainfall, an antecedent precipitation index, geology, and soil texture. Special equipment has been installed on the Haute-Mentue catchment to measure flow, rainfall and the chemical signature of waters. The chemical signature was defined according to samples collected with automatic samplers (ISCO Environmental Division, Lincoln, USA) for flow and for rain and with ceramic suction cups for soil water (Figure 2).

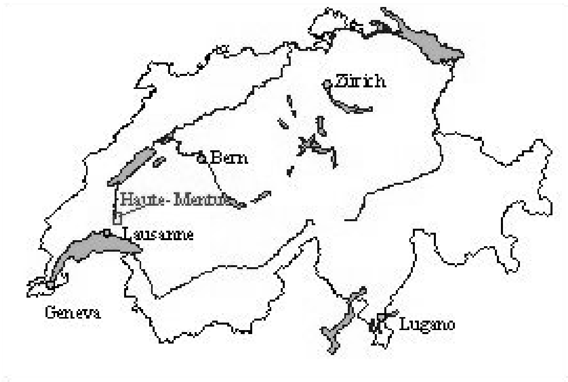

Figure 1: Geographical localization of the Haute-Mentue catchment.

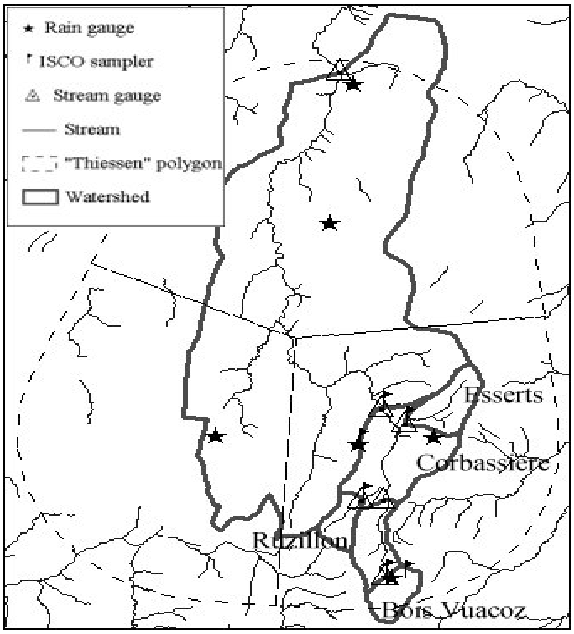

Figure 2: Experimental setup and delimitation of the Thiessen polygons.

2. MONITORING OF THE STREAM FLOW BY ENVIRONMENTAL TRACING

The environmental tracing results are used in a chemical mixing model, which considers run-off at the outlet as resulting from the mixture of three components: precipitation, soil water and groundwater. The tracers used to distinguish these three components are calcium and silica. Hydro-meteorological data were handled by the AIDH (Analyse d'Incertitude des Décompositions des Hydrogrammes) program, developed at IATE/HYDRAM. Based on Monte Carlo simulations, this program allows separation of hydrographs into three components while considering the uncertainty of the results due to the spatial and temporal variability of the component chemical signatures. According to the available information, the chemical signatures were defined by considering the temporal variability of the three components and also the spatial variability of the groundwater.

In the particular case of the Haute-Mentue, the precipitation component exhibits the smallest variability, with both calcium and silica having small standard deviations. The soil water component is less precisely defined, especially with regard to the silica variability. Hydrograph separations were repeated 1000 times, with each generation determining a new chemical signature for the three components. In this way it was possible to determine a statistical distribution of each component’s contribution. Hydrograph decompositions were compared for four catchments of the Haute-Mentue basin, with rainfall-runoff events from April 1998, September 1998 and October 1999 chosen for this analysis. Spring rainfalls exhibited maximum intensities at the beginning of the events while autumn rainfall showed most often maximum intensities in the middle and towards the end of rainfall events. The hydrograph separations showed that the split of component contributions to quickflow depends essentially on the meteorological conditions and on the physical properties of the basins. Indeed, there are no major differences in the hydrological response of the considered catchments when there are dry antecedent conditions.

In contrast, under humid antecedent conditions, hydrograph separations showed differences in hydrological behaviour on the Haute-Mentue catchment. For all catchments the soil water contribution increases, but to a different extent depending on their physical characteristics. Moreover, in the Bois-Vuacoz catchment, soil water has a very rapid response, and represents the most important component of the flood, even after dry antecedent conditions (Figure 3).

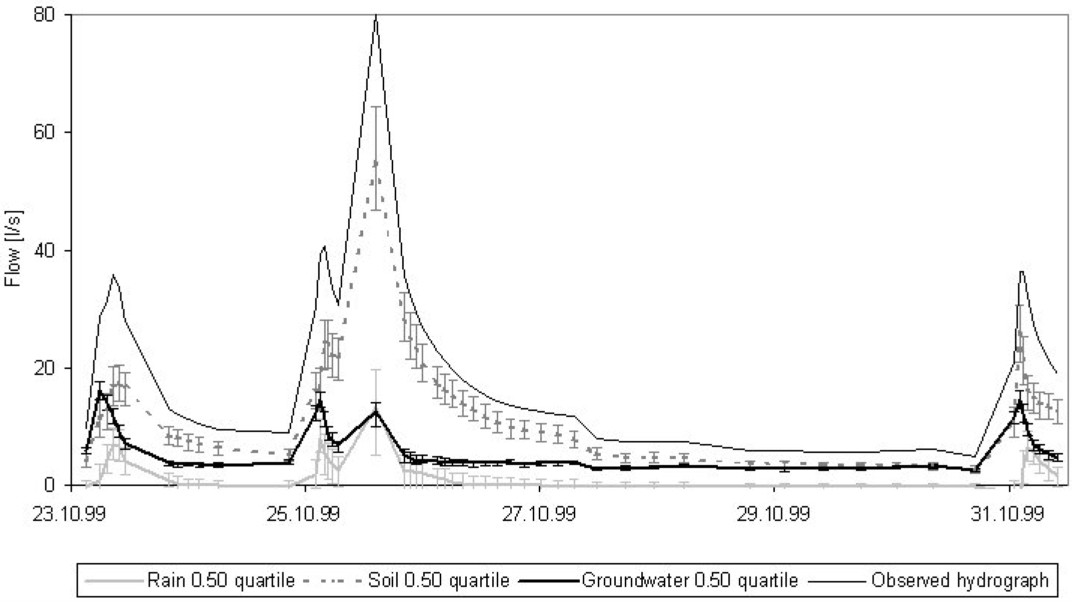

Figure 3: Environmental tracing: hydrograph separation and uncertainty.

This kind of monitoring allows identification of the general hydrological processes that occur at the catchment scale. Environmental tracing results tend to integrate at the basin scale, and downscaling is difficult when trying to identify the spatial variability within the catchment. In reality, spatial variability is important, and to understand better the catchment hydrological behaviour, it seems necessary to study the processes at the hillslope scale.

3. STATISTICAL MODELLING OF THE SUBSURFACE DISCHARGE

Statistical modelling was carried out in order to identify those physical parameters that influence the hydrological response at the catchment scale. All statistical treatments were done under the S-Plus environment. This analysis was based on seven rainfall-runoff events observed in 1998 in four nested subcatchments of the Haute-Mentue catchment. An average contribution of flood components was computed for each of these events. Multiple regression models and variance analyses were used to estimate the subsurface discharge function of quantitative and qualitative variables.

The explicit variables considered for the elaboration of statistical models were: the total precipitation (PP), the 10-day antecedent precipitation index (API), the lithology and the soil texture. The areal precipitation was computed by using the Thiessen method. To define the qualitative variables the physical properties of the lithological formations were weighted by their estimated hydraulic conductivity and their surface coverage within the catchment. The predictor variables were considered in both an additive and interactive way. A "main effect" is defined as the direct effect of an independent variable on the dependent variable, while an "interaction effect" is the joint effect of two or more independent variables on the dependent variable. The statistical models have been tested using ANOVA tables and the usefulness of the predictor variables has been quantified through the use of F- and S-tests. In all cases, the dependent variable was the total subsurface discharge as computed by the AIDH program.

Table 1: Statistical models comparison.

Statistic model	**Sum of squares**	**F-value**	**P-value**
Model 2 - 1	1249.631	5.764451	0.01010355
Model 4 - 2	1807.158	5.323045	0.00453903
Model 4 - 1	3047.79	7.345118	0.00087251

Several different models have been elaborated. The predictors in these models were: total precipitation in Model 1, total precipitation and the antecedent precipitation index in Model 2, total precipitation, the antecedent precipitation index and the soil texture in Model 4. The three models were compared using an ANOVA test and the results of this comparison are presented in Table 1. The small p-value obtained when comparing Models 1, 2 and 4 shows that Model 4 is the most significant (Figure 5). Model 4 was used further to analyze the correlation between observed and fitted values. It is demonstrated by the analysis of variance table that the most important predictors are: the soil texture, the precipitation and the interaction between the precipitation and the antecedent precipitation index. The quality of this model was checked by using the percentage of bias to estimate the deviation of the fitted values from the observed values: $I_{\%bias} = \sum\left(Q_{obs} - Q_{fit}\right)^2 \Big/ \sum\left(Q_{obs}\right) * 100$, where $I_{\%bias}$ should be equal to 0. For Model 4, this index is $I_{\%bias} = 0.0022$. The quality of the model was also verified with the Nash & Sutcliffe criteria: $NS = 1 - \left[\sum\left(Q_{obs} - Q_{fit}\right)^2 \Big/ \sum\left(Q_{obs} - Q_{moy}\right)^2\right]$, where *NS* should be equal to 1. For Model 4, the Nash & Sutcliffe is equal to 0.96. Both indices show a good fit for the Model 4 values.

Model 4 validation was achieved by predicting average soil contributions for three new rainfall-runoff events. The quality of the Model 4 predicted values was also checked using the same two criteria, and the obtained results were $I_{\%bias}$ = -0.80 and *NS* = 0.93. Even for the predicted values, both criteria show good fit, however the percentile of bias indicates a slight underestimation of the predicted soils contributions compared to the observed soil contributions. The statistical approach highlighted the importance of the lithology and the pedology in explaining the spatial variability of the subsurface discharge at the catchment scale (Figure 4). For the future, more appropriate techniques of upscaling and estimating the physical properties of the catchments will have to be developed and introduced to the hydrological modelling.

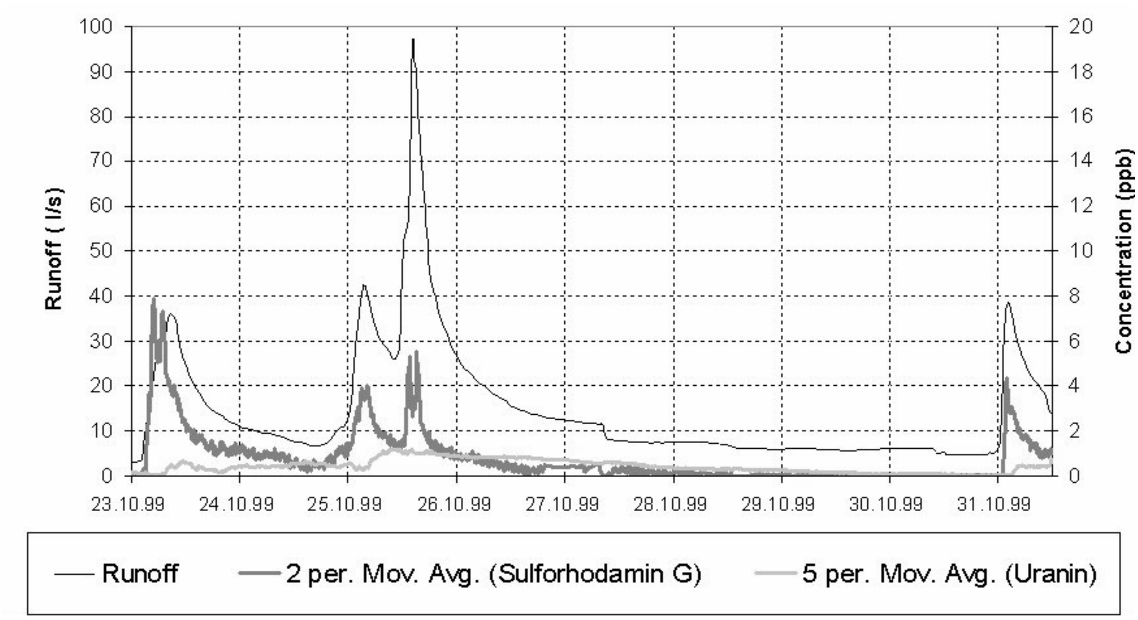

Figure 4: Dye tracing: monitoring of the subsurface runoff at the local scale.

4. MONITORING OF SUBSURFACE FLOW BY USING DYE TRACING

To highlight the hydrological processes that might occur at a local scale, and more particularly to explain the rapid response of the soil water during a flood event observed during the hydrograph separation, a dye tracing was carried out in October 1999 on the Bois-Vuacoz catchment. Dye tracing experiments in the soil horizons have already been carried out on the field in Switzerland using a rainfall simulator with intensities of 60 -100 mm h^{-1}, but never under conditions of natural precipitation as proposed here. The artificial tracing was complemented by environmental tracing, with the idea of comparing the results of the two experiments. The experimental site was equipped with two fluorimeters, one at the outlet, and the second 26 m up the stream. Two ranges of three deep piezometers (at 100 cm, at the soil / bedrock limit and at 50 cm) and three near subsurface piezometers (at 40 cm, at the soil upper permeable A horizon / more clayey B-horizon) have been installed on the left bank of the stream 12 m away from the river. The rainfall exhibited the typical characteristics of autumn events, with longer duration and with greater intensities at the end of the events.

In this experiment two dyes were used: uranin and sulforhodamin G. This choice was motivated by:

- the aim of the experiment, which is the identification of soil water response under real rainfall conditions at two different depths;
- the type and the technical limits of the available field fluorimeters;
- the tracer properties of the uranin.

The tracing results were obtained directly in the field by using the fluorimeter GGUN and in the IATE/ HYDRAM laboratory using the spectrofluophotometer RF-1501. This experiment showed that sulforhodamin G restitution curve (50 cm depth injection) faithfully follows the flood hydrograph. The uranin (100 cm depth injection) however started to react later (Figure 5). One conclusion is that subsurface runoff is apparently preferential, its temporal behaviour depending on the soils properties and on the input characteristics. As confirmed by the laboratory results, the soil hydrological behaviour gave evidence of a two-level, soil runoff pathway, with a delayed contribution during the flood. In Table 1 we tried to compare the principal characteristics of the two experimental methods, considering both the scientific and technical aspects of soil runoff contribution to the flood. Identification of the soil water pathway at the hillslope scale is the main advantage of this kind of experimental approach. Artificial tracing is a complementary approach to environmental tracing, giving information with regard not only to the temporal contribution of the soil water but also to the vertical distribution of the soil water pathways.

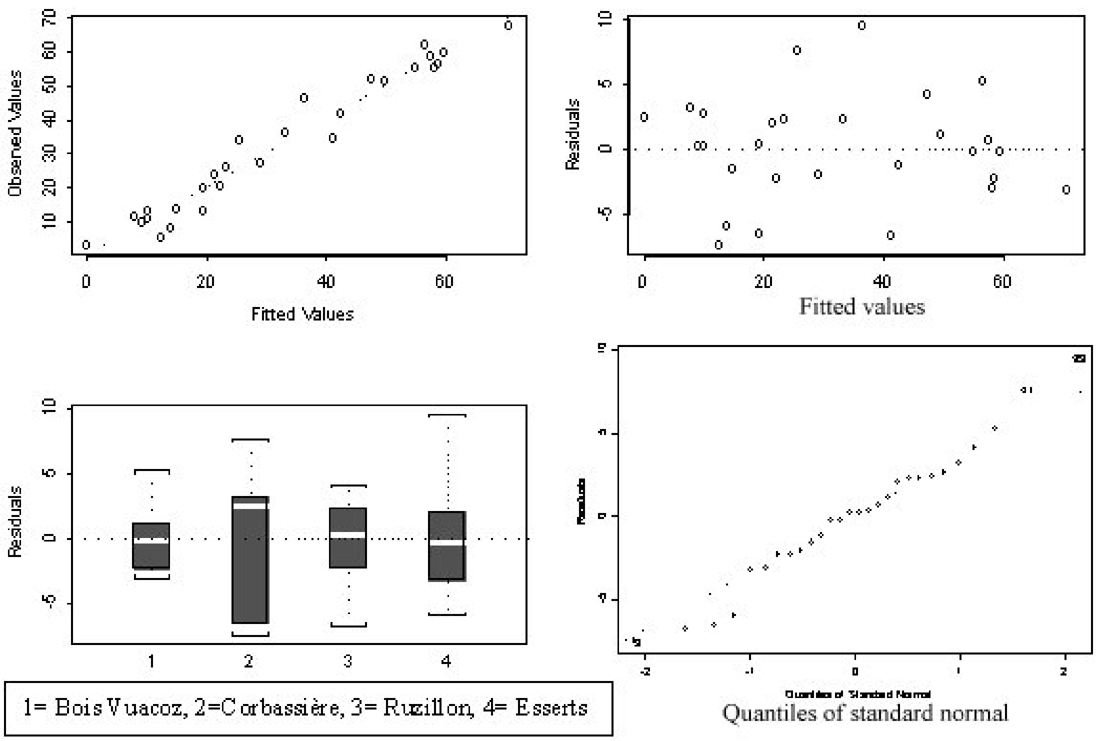

Figure 5: Diagnostic plots for the multiple regression model no. 4: “Soil contribution function of total precipitation, antecedent precipitation index and soil texture”.

5. CONCLUSIONS

Environmental tracing allows the monitoring of runoff components at the catchment scale, however downscaling remains difficult because of spatial variability within the catchment. Statistical models with qualitative variables can account for the spatial variability between the catchments and demonstrate the importance of the basin physical properties in explaining the hydrological response. Dye tracing confirmed the environmental tracing results at a local scale, with special regard to the temporal contribution of the subsurface runoff and to the vertical distribution of the soil water pathways. The conjoining of different types of measurements that can furnish information at different scales, as demonstrated in this study, seems a very promising approach to better identification of hydrological processes.

Table 2: Tracer techniques comparison.

Environmental tracing	Artificial tracing
Catchment scale	Hillslope scale
Quantitative and temporal evolution Estimation of the soil runoff without considering the soil water pathways	Qualitative estimation of the soil runoff by considering the soil pathways identification
Non pollutant method	Locally pollutant method
Subsequent laboratory handling	None subsequent laboratory handling
Continuous but with a sequential sampling rate of 100 m^3	Continuous sampling: 4 minutes sampling rate
Uncertainty due to missing samples and to laboratory analysis	Higher uncertainty due to the turbidity effect on the dyes signals
Possibility of the uncertainty estimation	Unknown method to estimate real concentration

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Conference on “Monitoring and Modelling Catchment Water Quantity and Quality”
Ghent, Belgium, September 27-29, 2000

Surface water quantity and quality modelling by the complementary use of detailed and simplified models: Case studies of Dender and Witte Nete watersheds

Willems, P., M. Radwan, D. Popa, A. El-Sadek & J. Berlamont

Hydraulics Laboratory, Katholieke Universiteit Leuven
Kasteelpark Arenberg 40, B-3001 Leuven, Belgium
Email: Patrick.Willems@bwk.kuleuven.ac.be

ABSTRACT

To model the flow and water quality of surface waters accurately, those waters have to be described in an integrated way taking into account several sources of water and pollution. The different man-made and natural systems that are connected to these sources have to be linked with the surface water model. Examples of these are sewer systems, waste water treatment plants (WWTP) and hydrographical catchments. A methodology for such modelling is presented, which combines detailed and simplified models for the various subsystems. The models are built up for each subsystem taking into consideration the balance between model detail and data availability. More specifically, to avoid overparameterization of the model structure, the model detail is selected for each subsystem by balancing the fundamental and the operational uncertainties. To save on calculation time and computer memory requirements, simplified models can be calibrated to these detailed models. The simplified models for the various subsystems are then linked in order to construct a holistic watershed management model. To validate this holistic model, observed and simulated frequency distributions are compared, using long-term continuous simulations (total duration of 100 years).

1. INTRODUCTION

To model the flow and the water quality of the surface waters in the hydrographical catchment, different model types are available. These vary from detailed physically-based models to simplified conceptual and empirical models. The most appropriate model type for a certain application depends on the project objectives and the data availability. Whenever different model types with different modelling detail are compared, the most appropriate model to meet the project objectives must have an optimal balance between uncertainties resulting from model assumptions (or fundamental uncertainties) and uncertainties resulting from the data (or operational uncertainties). This is schematically represented in Figure 1. The balance therefore depends on data availability, as the optimal model detail and also the model accuracy increases with increasing data, although implementation costs will also increase (as indicated by the third axis in Figure 1).

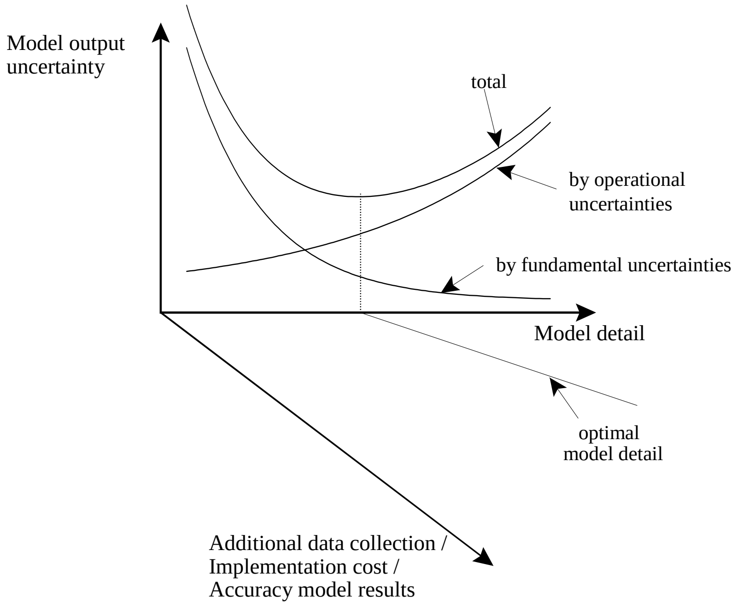

Figure 1: Balancing different types of uncertainties to determine the optimal model-structure detail.

A surface water model comprises different submodels: the hydrological models of the different subcatchments, the hydrodynamic and water quality models of the surface waters and the submodels for the different water and pollution sources. These latter sources consist of WWTP effluent discharges, sewer system overflow emissions, industrial discharges, diffuse agricultural pollution and untreated diffuse domestic discharges. For some submodels, more data are available and a more detailed model can be implemented. This is most often the case for the hydrodynamic models. In Belgium, for instance, detailed full hydrodynamic models can be built for most rivers and sewer systems with high accuracy and reasonable cost. However, such models have a large calculation time. Although these models are very useful for short-term simulations of representative (historical or synthetic) events used to analyse an observed surface water state, they are not appropriate for long-term simulations, for deriving long-term statistical information about the surface water state, or as management tools. For these purposes, a more simplified (conceptual or meta-) model can be used in a complementary way to calibrate the detailed model.

2. METHODOLOGY

2.1. Modelling of subsystems

In this paper, the principles described above have informed a methodology that has been worked out by the authors and applied to two Belgian river basins. In the large basin of the river Dender (708 km^2), the hydrology and hydrodynamics have been modelled for the 12 subbasins, the river Dender and 5 brook-tributaries (total distance of 157 km watercourses). The subbasin of the Molenbeek brook (57 km^2) has been modelled separately in more detail. Subsequently, a simplified model was calibrated by the derived detailed model, and used for the larger Dender basin. In addition a water quality model was calibrated for the Molenbeek subbasin. The diffuse agricultural pollution was described on the basis of a nitrate leaching model, while the industrial and untreated domestic pollution sources were estimated empirically. In the second watershed of the Witte Nete (40.7 km^2), the emissions of a WWTP and a combined sewer overflow (12376 population equivalents) were modelled.

An overview of the different subsystems and modelled processes is given in Figure 2a. For all the subsystems listed in this figure, the model types selected in the case-studies for both the detailed and simplified models are summarized in Figure 2b. For some systems, detailed models were not considered appropriate with respect to the uncertainty considerations illustrated on the basis of Figure 1. For these systems, therefore, only the simplified model types are considered appropriate. Whenever the detailed or simplified modelling methodology was largely based on an existing methodology, this is indicated in the figure by a standard reference.

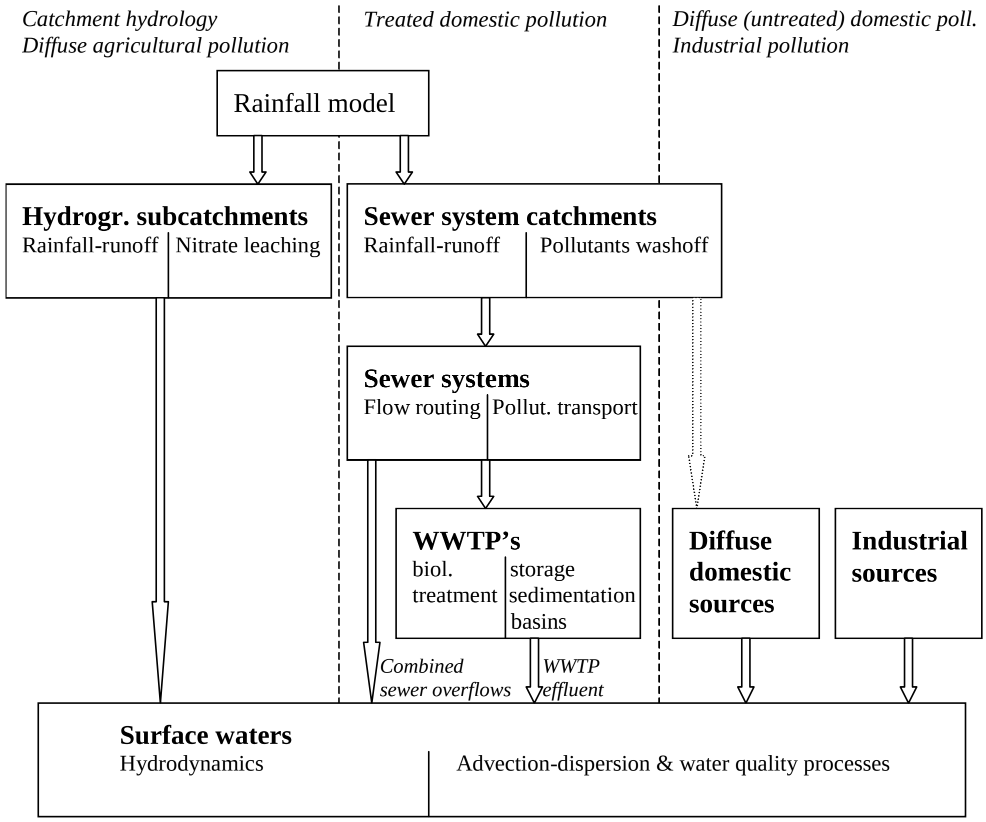

Figure 2a: Overview of the different subsystems involved in the surface water quantity and quality modelling.

As indicated in Figure 2b, implementations of the modelling systems MIKE11 (Danish Hydraulic Institute) and ISIS (HR Wallingford) were used as detailed hydrodynamic models. MIKE11 was also used for the detailed water quality description. The Hydroworks modelling system (Wallingford Software) was implemented for the detailed flow modelling in sewer systems. Linear transfer function models were applied to the simplified modelling of all the systems listed in Figure 2. Although the general linear transfer function model type is often used as an empirical model, it can be given a physical interpretation on the basis of the linear reservoir modelling concept. The reservoir model is able to describe the relationship between the upstream storage (of water or pollutant mass) in the system and the discharges or concentrations at one specific point in the system. For the subsystems connected to the river system only the emissions have to be modelled. This point can therefore be chosen as equal to the emission point, which will most often be the downstream limit in the system. For the rivers, intermediate points also have to be considered. This can be achieved using a serial and/or parallel connection of reservoirs.

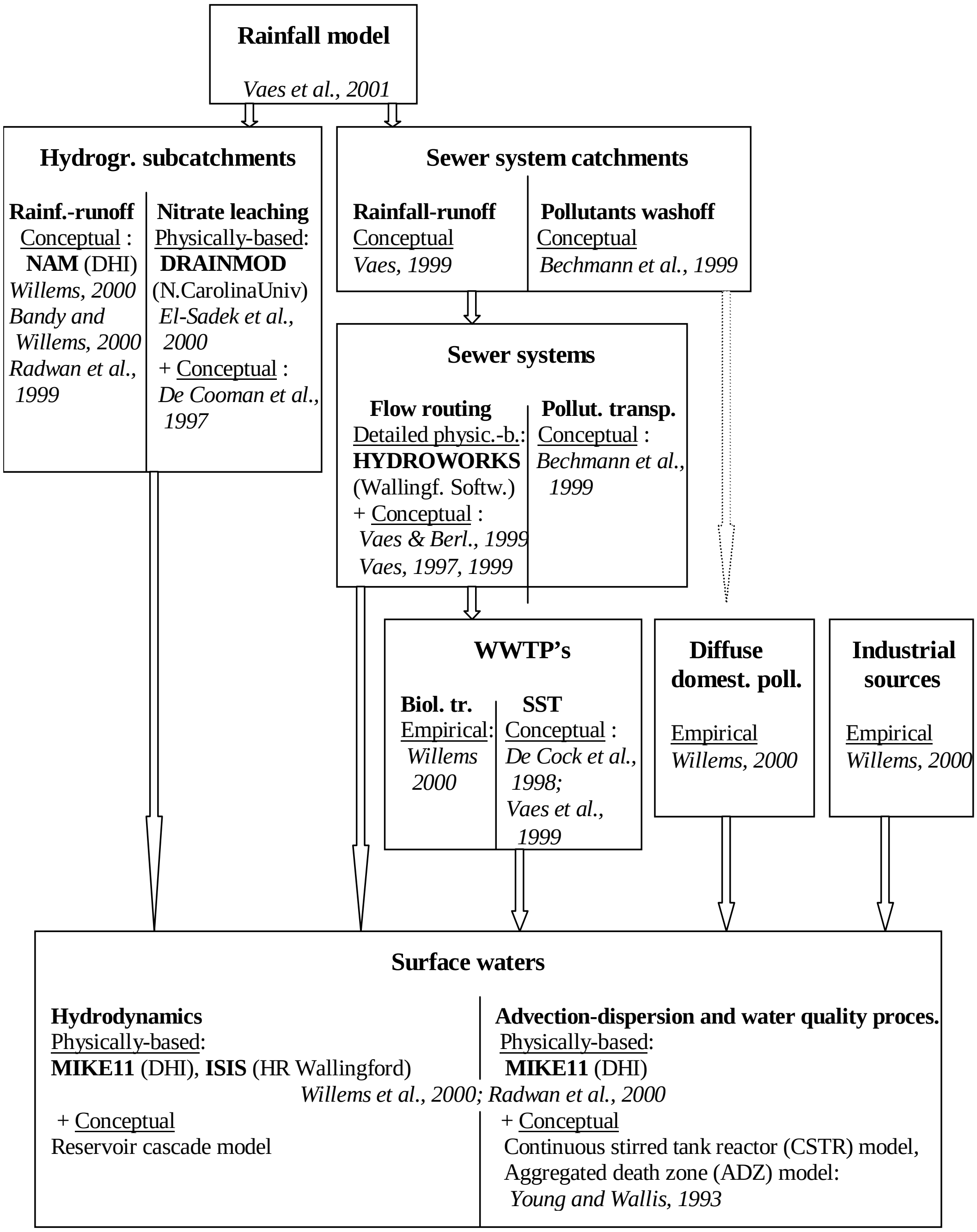

Figure 2b: Overview of the detailed and simplified model types used for the different subsystems of Figure 2a (model types underlined, existing modelling systems in bold, references to modelling methodologies in italic).

These are called 'conceptual models'; they are based on the physical interpretation of the simplified models and can be calibrated in a physically-based way. As an example, the reservoir model for the flow in the sewer system was calibrated by parameterizing the storage-throughflow relationships derived from simulations using the detailed model (Vaes &

Berlamont, 1999). The simplified model structure was identified and calibrated simultaneously making optimal use of the physical interpretation given to the model structure.

2.2. Simulations with the holistic model

By linking the simplified models for all subsystems, an integral (or holistic) watershed model can be built, which can then be used for long-term simulations, and thus as an efficient watershed management tool. Such watershed management models have been set up for the two case-studies mentioned. Two types of simulations were performed, each with an hourly time step. In a first simulation, historical rainfall, spatially-averaged for each subsystem catchment, was used for calibration, for the period for which hourly and daily rainfall data measurements were available. The hourly rainfall series that is closest to the catchment centre was used to distribute the more dense daily rainfall data. When rainfall continues from one day to another, the daily rainfall is averaged for two or more successive days, to avoid errors caused by time lags in the rainfall records at the different stations.

After calibration and validation of the model using this rainfall input, a second long-term simulation was performed using the 100 years rainfall series available at the main Belgian meteorological station at Uccle (from 1898). This enabled a statistical analysis of the state of the surface waters. The simulated discharges and DO, BOD, NH_4-N and NO_3-N concentrations were evaluated in comparison with emission standards that exist for both pollutant concentrations and hydrological conditions (e.g. return period of flooding). Amplitude/duration/frequency relationships were developed from the long-term simulation results (see also Vaes *et al*., 2000). The amplitude equals the water level or the discharge for flooding studies, or the concentration or load for water quality studies. In comparison with extreme value distributions, the amplitude/duration/frequency relationships also consider the ‘time duration’ factor. This is relevant to both flooding and water quality problems. The concentration or recession time of the hydrographical catchment, the river or the sewer system determines the time during which the cumulative rainfall volumes cause flooding problems. In terms of water quality, the time during which the concentration thresholds are exceeded determines the type and degree of deterioration in the aquatic life.

3. MODELLING RESULTS

An example of the statistical processing of the model results is shown in Figure 3, where the analysis has been done on the basis of frequency distributions derived from the long-term (100 years) simulation results of river discharges (in Figure 3a, Molenbeek subbasin) and DO concentrations (in Figure 3b, Witte Nete watershed). The independent extremes in the figures are derived from the time series by applying an independency criterion, whereby exceedences of the standards, and the corresponding effects on the surface water state, are considered independent when they are separated by a time span of at least 12 h.

4. CONCLUSIONS

It is shown in the case of both discharges and concentrations that the model can be validated on the basis of a comparison with measurements. The matching of the simulated and observed frequency distributions shows that the model is able to describe accurately the long-term statistical properties of the surface water states. The similarity in shape of the tails of the distributions shows moreover that the model performs well when extrapolating to extreme events not originally included in the model calibration. Such a validation on a limited number of historical events is a useful adjunct to the traditional forms of calibration and validation. However, it needs a long-term simulation, which can only be performed using simplified models as surrogates to the standard detailed system models.

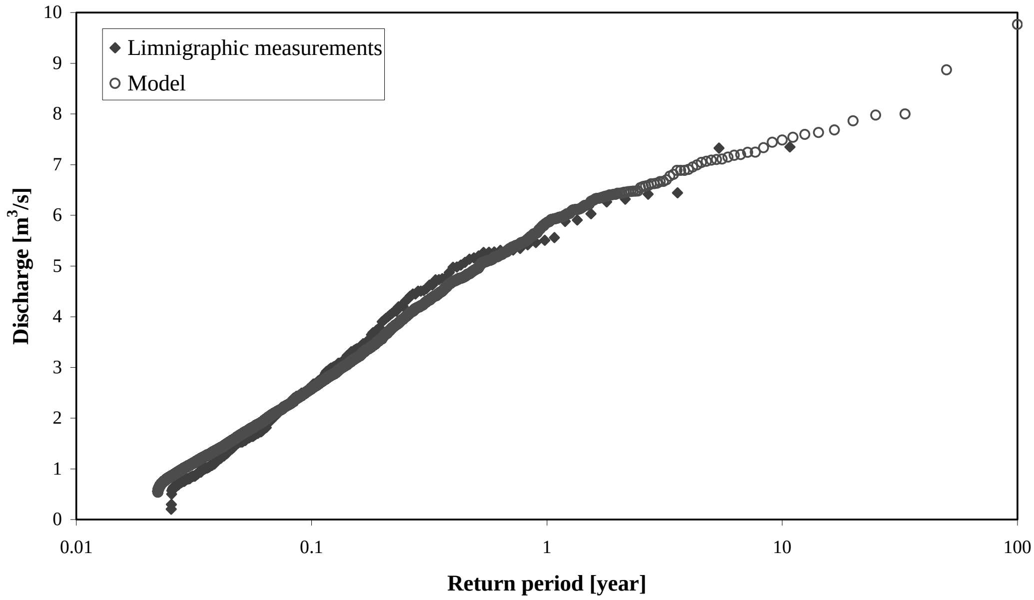

Figure 3a: Example of model results in terms of the frequency distribution of river discharges; Molenbeek subbasin; model simulation with historical rainfall series at Uccle (1898-1997), limnigraphic measurements for 1986-1996.

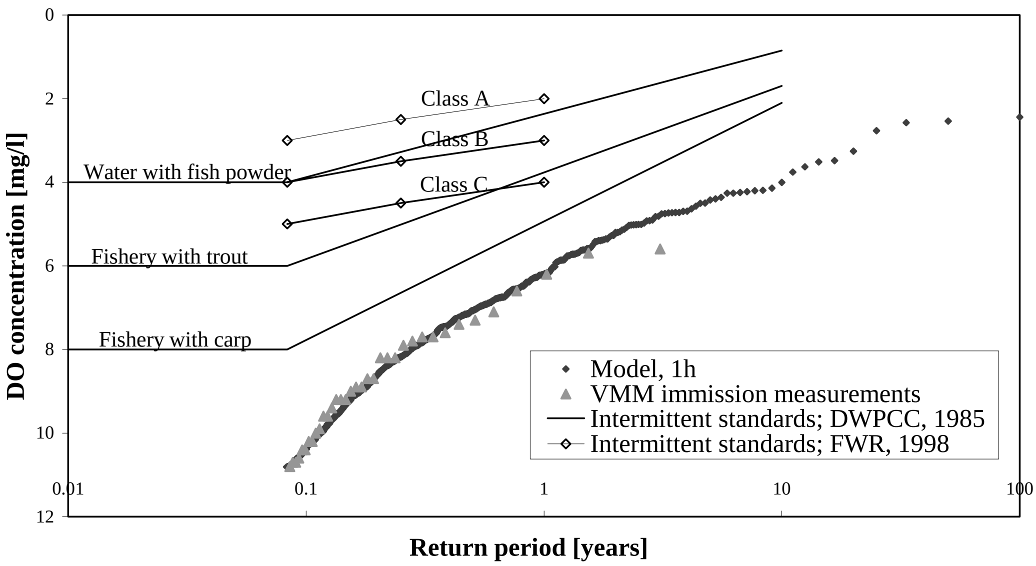

Figure 3b: Example of model results in terms of the frequency distribution of DO concentrations; Witte Nete watershed; model simulation with historical rainfall series at Uccle (1898-1997), immission measurements of the Flemish Environmental Agency (VMM).

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