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Anomaly in the rainfall-runoff behaviour of the Meuse catchment. Climate, land-use, or land-use management?

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Abstract. The objective of this paper is to investigate the time variability of catchment characteristics in the Meuse basin through its effect on catchment response. The approach uses a conceptual model to represent rainfall-runoff behaviour of this catchment, and evaluates possible time-dependence of model parameters. The main hypothesis is that conceptual model parameters, although not measurable quantities, are representative of specific catchment attributes (e.g. geology, land-use, land management, topography). Hence, we assume that eventual trends in model parameters are representative of catchment attributes that may have changed over time. The available hydrological record involves ninety years of data, starting in 1911. During this period the Meuse catchment has undergone significant modifications. The catchment structural modifications, although documented, are not available as "hard-data". Hence, our results should be considered as "plausible hypotheses". The main motivation of this work is the "anomaly" found in the rainfall runoff behaviour of the Meuse basin, where ninety years of rainfall-runoff simulations show a consistent overestimation of the runoff in the period between 1930 and 1965. Different authors have debated possible causes for the "anomaly", including climatic variability, land-use change and data errors. None of the authors considered the way in which the land is used by for instance agricultural and forestry practises. This aspect influenced the model design, which has been configured to account for different evaporation demand of growing forest. As a result of our analysis, we conclude that the lag time of the catchment has decreased significantly over time, which we attribute to more intensive drainage and river training works. Furthermore, we hypothesise that forest rotation has had a significant impact on the evaporation of the catchment. These results contrast with previous studies, where the effect of land-use change on the hydrological behaviour of the Meuse catchment was considered negligible, mainly because there was not sufficient change in land cover to account for it. Here we hypothesise that in the Meuse it was not the change of land cover that was responsible for hydrological change, but rather the way the land was managed.

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1 Introduction

The Meuse river basin extends over an area of 33 000 km^2 which covers parts of France, Belgium, Luxembourg, Germany and the Netherlands (Fig. 1). During the past century, this catchment has faced several modifications which may have influenced its hydrological behaviour (de Wit, 2009; Nienhuis, 2008). In general the catchment has undergone substantial change as a result of population development, migration and economic development. Changes in land cover and land-use involved urbanization, industrialization, afforestation, deforestation, intensification of agricultural practices, construction of storage works and increase of drainage efficiency (Nienhuis, 2008; Garcier, 2007). The drainage improved in agricultural fields, in urban areas and also in forests as a result of forest road construction. Road construction in general can have a marked influence on drainage, particularly during peak events (e.g., Hollis, 1975). Also the drainage efficiency of the water courses improved as a result of river rectification and building of weirs, locks and canals (de Wit, 2009). An impact seldom mentioned is the effect of different

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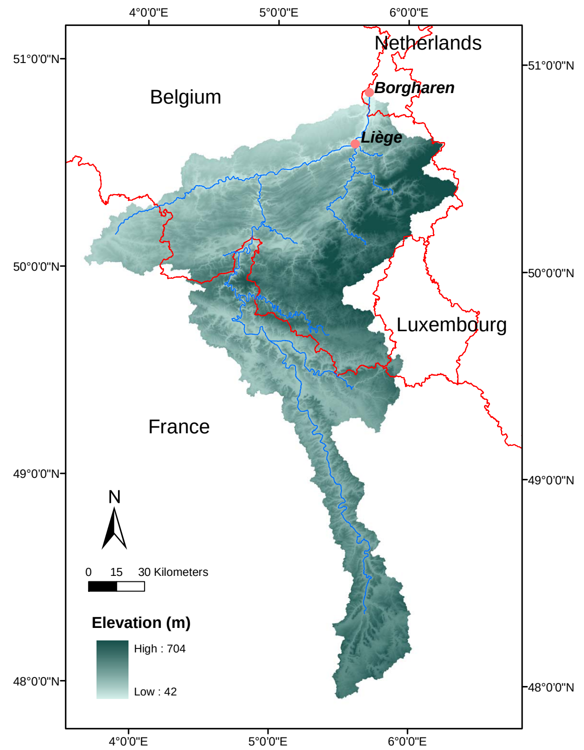

Fig. 1. Location of the Meuse catchment.

land-use management strategies, which primarily relates to the ways in which agricultural areas and forests are tilled, cropped and harvested.

After severe floods in the Meuse in 1993 and 1995, a meeting was held at the EGU in 1995 on the possible causes of the extremity of these floods (Savenije, 1995). The opinions of authors could be grouped in: 1) nothing out of the ordinary happened; it is part of the natural variability (Ulbrich and Fink, 1995); 2) there are trends visible indicating more intensive floods in recent years, indicating at climatic change (e.g., Black, 1995; Bronstert, 1995; Caspary, 1995); and 3) there is a significant effect of human interference due to more intensive drainage, road construction and river training (Savenije, 1995). Since then, the effect of climate and land-use change on the behaviour of the Meuse catchment has been subject of several studies. The daily record of hydrologically useful information starts in 1911, and it has been shown that the rainfall-runoff relation of this catchment has experienced significant alterations (Tu Min et al., 2005). However, whether the observed changes in hydrological behaviour should be attributed to human induced change, or to climate variability, or that they are simply an effect of the large uncertainties in the data was not well understood.

Tu Min et al. (2005) applied change point analyses to investigate the temporal change in the flood peaks of the Meuse River over the past century, accounting for the potential effects of climate and land-use change. They determined that both the antecedent (7-days) precipitation depth and the flood peaks increased significantly since the 1980s, while the land cover remained relatively stable during the past century. They concluded that the increase in high flow events should be attributed primarily to climate variability rather than to land-use change.

Ward et al. (2008) performed a hypothetical experiment where they coupled a climate model and a hydrological model to simulate daily discharge during several millennia. They determined that, while on a long-term (millennial) time scale land-use change has a strong impact, in the 20th century the main driving mechanism responsible for changes in hydrological behaviour is climate change. In addition, they noticed that the observed reforestation over the last century should theoretically have led to decreased discharge and that the main mechanism responsible for the larger flood peaks in the latest years is increased precipitation. Increases in annual and winter maximum daily discharge and precipitation were also demonstrated in the neighbouring Alzette catchment in Luxembourg by Pfister et al. (2000).

Building on the work of Booij (2005), Ashagrie et al. (2006) investigated the effect of land cover change within the catchment by using a semi-distributed conceptual model (HBV). According to their analysis, the main change in land cover was a shift from deciduous to coniferous forest, while the total forest cover and agricultural land remained relatively stable. They calibrated the model during the years 1911–2000, and they found out that while the observed discharge was well represented at the beginning and at the end of the simulation period, a consistent overestimation occurred in the central part of the observation record (between years 1933 and 1968) (see Fig. 2). This deviation in discharge volumes could not be explained by a change in forest types.

To test if the anomaly was due to data errors, Ashagrie et al. (2006) performed the same analysis on the Moselle catchment, which neighbours the Meuse on the east and has similar size, history and physical characteristics. Surprisingly, the analysis produced similar results, with even larger systematic deviations in the central part of the observation record. As the data of the two catchments can be considered independent, it can be hypothesized that such systematic deviation is not merely a consequence of data errors, but it is the result of processes, mechanisms or catchment structural modifications that were not identified in previous studies.

Overall, these studies suggest that land-use changes have had a negligible impact on the hydrological behaviour of the Meuse catchment. Climate change, in contrast, is seen as the dominant control. However, while climate change may account for the increased flood peaks of the last decades, it cannot explain the anomaly in the rainfall-runoff relation identified by Ashagrie et al. (2006). This motivated the investigation of additional hypotheses of catchment behaviour, which is the main purpose of this work.

In Belgium, during the 19th century, heathlands were converted into deciduous forest and arable land. Afterwards, coniferous forests were converted into rapidly growing deciduous plantations (Lambin and Geist, 2006). Petit and Lambin (2002) performed a historical reconstructions of land cover change of a Belgian landscape in the Ardennes. The major land-cover change processes observed are expansion of grasslands-croplands and reforestation with coniferous species. According to their analysis, the land-cover changes were maximum between 1923 and 1957. The area investigated by their study is much smaller than the total catchment area. However, it exactly corresponds with the period of interest for the "anomaly".

Although it is difficult to obtain full information on the developments that have taken place over such an extended period of time, it can be argued that the gradual shift from deciduous to coniferous forest was accompanied by a change in forest management policy as well. An important hydrological parameter in forest management is the rotation of the stands, since forest age is linked to the actual transpiration of the trees. There is in fact an increasing body of evidence that young forest evaporates considerably more than mature forest (e.g., Kuczera, 1987; Vertessy et al., 2001; Watson, 1999).

The purpose of this work is to assess the possible impacts of human interference (not only of forest management) on the rainfall-runoff behaviour of the Meuse basin. The approach adopted consists of using a conceptual model which is dynamically evaluated over time in order to detect temporal trends or change points in model parameters. The model is constructed in a way that it includes parameters that explicitly refer to leaf conductance, parameters which were considered constant in previous studies, as is commonly done in hydrological modelling applications. The model evaluation framework is based on the dynamic identifiability analysis proposed by Wagener et al. (2003). Subsequently, we try to relate trends in parameter values to changes that may have occurred in the catchment.

The paper is organized as follows. We first present a description of the catchment and data, then we describe the model structure and set up, then we introduce the model evaluation framework and finally we present and discuss the results.

2 Study area and data description

The study area is the Meuse basin upstream of the gauging station of Borgharen, which covers an area of approximately 21 000 km^2. The Meuse basin is characterized by a rainfall-evaporation regime, which produces low flows during summer and high flows during winter. Mean annual precipitation over the basin is 950 mm/a, and is reasonably uniformly distributed throughout the year, while potential evaporation has a strong seasonal trend, with higher values during summer and lower values during winter (de Wit et al., 2007).

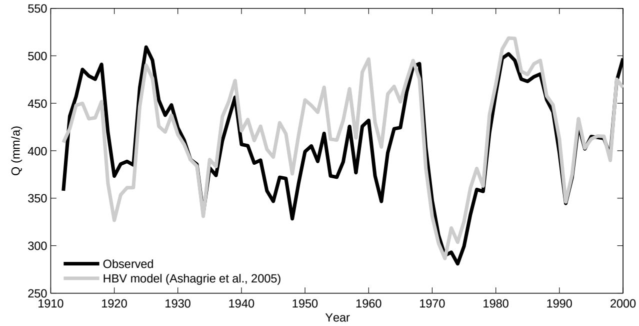

Fig. 2. Comparison of observed and simulated hydrograph after Ashagrie et al. (2006). The observed discharge appears to be considerably overestimated in the central part of the observation period.

The lithology of the catchment is characterized by three main zones. The southern part of the basin is dominated by sedimentary consolidated rocks. The central part belongs to the Ardennes Massif, and consists of methamorphic rocks which are relatively impermeable. The northern part of the basin consists of lowlands characterized by sedimentary, unconsolidated rocks. Hydrologically useful information is available starting from year 1911 and consists of daily values of discharge measured at Borgharen (www.waterbase.nl), meteorological variables measured at De Bilt in the Netherlands, and precipitation amounts from several raingauges in the catchment (Ashagrie et al., 2006).

The discharge at Borgharen is affected by extraction of water which is diverted outside the basin. The observed time series were corrected for these canal extractions (Ashagrie et al., 2006). However, detailed information was available only after 1990. Prior to this date the water extraction has been estimated on an annual basis, and has been set at a fixed rate (Ashagrie et al., 2006). Moreover, the discharge of the Meuse river is influenced by the operation of weirs and reservoirs, which particularly affect discharge during low flows. In fact, the Meuse river is navigable over a substantial part of its total length, connecting the Rotterdam-Amsterdam-Antwerp port areas to the industrial areas upstream. During low flow periods the weirs are operated to maintain a minimum stream level for shipping.

Meteorological data required to determine potential evaporation were obtained from the station of De Bilt, located 180 km north of Borgharen (www.knmi.nl). They include relative sunshine duration, wind speed, air temperature, and relative humidity. These data were used to determine the potential evaporation with the Penman-Monteith equation. Observations of meteorological variables within the catchment area were not available for the entire observation period. However, we compared temperature records from De Bilt and Uccle (south of Brussels, in Belgium). In addition, we compared the potential evaporation calculated using temperature alone (with the Thornthwaite formula). The yearly averages are shown in Fig. 3, demonstrating a good general agreement.

Precipitation is available at seven stations within the catchments. Information about the location and the quality of the data can be found in Ashagrie et al. (2006). For this study the rainfall series have been averaged over the entire basin using the Thiessen polygon method.

According to the CORINE data base (http://reports.eea.europa.eu/COR0-landcover/en), land-use in the Meuse catchment at present consists of 34% agricultural land, 20% pasture, 35% forest, 9% built-up area, and 2% wetlands. Data on historical land-use change are not readily available at the basin scale, but can be reconstructed combining information from various areas within or in the proximity of the catchment (e.g., Petit and Lambin, 2002).

In the Walloon Region of Belgium, which includes part of the Meuse catchment, it has been estimated that the total forest cover did not vary considerably during the past century, consisting of about 30% of the total area of the region (DGRNE, 2000). However, the forest composition changed significantly. The extension of artificial coniferous forest increased from 30% to 50% of the total forest cover between the years 1929–1984, and decreased slightly afterwards, in tune with the expansion and decline of heavy industry and mining in the region. Production forest, after a period of very strong expansion, has stabilized and is now probably in decline (DGRNE, 2000).

Farmland covers about 45% of total area of the Walloon Region, and did not vary significantly over time (DGRNE, 2000). According to Tu Min et al. (2005), in the Lorraine-Meuse the portion of farmland used for agriculture showed a decreasing trend until the 1970s, after which it started to increase. An opposite trend is seen in the remaining part, primarily used for pasture.

The urban expansion triggered by the industrialization process has been very rapid during the 19th century, and progressed at a slower rate during the first part of the 20th century. It can be considered that the region was already highly urbanized by the 1950s, with a proportion of urban land of about 10–13% of the total catchment area (Tu Min et al., 2005). The construction of sewer systems and road networks progressed together with urban expansion, however, until the 1950s waste water was discharged into the natural environment without treatment. The construction of large treatment plants began only after the 1960s (Nienhuis, 2008; Garcier, 2007).

3 Methodology

The assessment of the effect of land-use change on rainfall-runoff behaviour has been the subject of several studies and remains an area of active research (DeFries and Eshleman, 2004). Different approaches have been employed to investigate this problem. The most widespread is based on observations and consists of paired catchment experiments. Two neighbouring catchments are monitored simultaneously, and

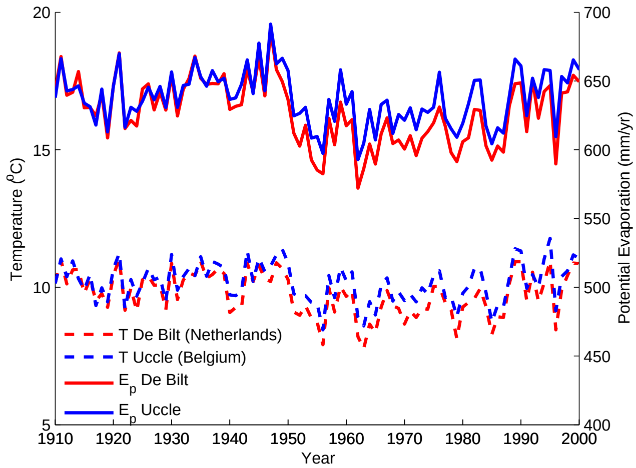

Fig. 3. Yearly averaged temperature and potential evaporation from De Bilt (Netherlands) and Uccle (Belgium).

following a calibration period one of the catchments is subjected to treatment while the other remains as control (e.g. Brown et al., 2005). This approach has several advantages, as it allows filtering out climate variability and it enhances the understanding on hydrological processes and their interaction with land-use. However, its application is limited to relatively small catchments, and the results are difficult to generalize.

Another common approach concerns the use of hydrological models. Model parameters are designed to represent specific catchment characteristics, and changes in land-use are then interpreted based on parameter variation. Following this approach, Eckhardt et al. (2003) performed a sensitivity study of the parameters affecting land-use of a distributed model. Lorup et al. (1998) and Schreider et al. (2002) calibrated a model in a period where there is no land-use change and compared it to a subsequent period where land-use change had taken place. Hundecha and Bardossy (2004) adopted a regionalization approach to relate model parameters to land-use characteristics to gain understanding on the effect of land-use change on runoff.

In contrast to previous modelling studies which required prior knowledge of the type of land-use change which occurred during the time considered, we here adopt an approach that is fully "top-down", and may be useful for catchments where little information is available on structural modifications. The approach is based on the model identification framework proposed by Wagener et al. (2003), which consists of a dynamic model evaluation in a moving time window. Our purpose is to extract significant trends in model parameter values which may then be related to land-use change. This approach provides continuous analysis of the time series and allows the identification of change points in hydrological behaviour.

3.1 Model description

The model used in this study is based on the FLEX modelling approach (Fenicia et al., 2007), and is composed of reservoirs and transfer functions which can be combined to generate different configurations. The structure used in this study is represented in Fig. 4. It consists of an interception reservoirs (IR, associated to different land-uses), an unsaturated soil reservoir (UR), a fast reacting reservoir (FR) and a slow reacting reservoir (SR).

Five land-use types have been considered: agricultural land, pasture, deciduous forest, coniferous forest, and built-up area. To each of these land-use types an interception threshold $I_{\max}$ is assigned (Savenije, 2004). All thresholds are then multiplied by a calibration parameter C_i, in order to allow them to vary proportionally. Interception thresholds of coniferous forest, pasture and built up areas are given a constant value while those of agriculture and deciduous forest are allowed to vary between a minimum in winter and a maximum in summer increasing or decreasing continuously in autumn and spring respectively (Table 1).

Water that exceeds interception (P_u) is routed through UR. Part of it infiltrates, and the remaining part (Q_q) runs off. Q_q is then partitioned in P_f and Q_p (representing preferential recharge). P_f is convoluted through a triangular transfer function, whose base is defined by the parameter N_{lagf}. The resulting flux P_{fl} is then routed through the linear reservoir FR. Percolation from UR (Q_u), and preferential recharge (Q_p) are summed (P_s) and routed through the linear reservoir SR. The fast (Q_f) and slow (Q_s) discharges are then added together. The closure relations for the different reservoirs are reported in Table 3, model parameters are reported in Table 4.

Potential evaporation has been calculated with the Penman-Monteith equation using measured wind speed, sunshine duration, relative humidity, and air temperature (Table 2). Differences between evaporation characteristics of the various land types have been introduced by using different values of aerodynamic resistance (r_a) and canopy resistance (r_c). The energy available for evaporation from interception ($E_{i,p}$) has been calculated assuming zero r_c (Asdak et al., 1998). Transpiration from different types of land cover ($E_{t,k}$, k: land-use type) has been determined assuming different values of r_c which for the forest area were multiplied by a calibration parameter α. The parameter α accounts for the fact that forest transpiration may vary with stand age. According to our parametrization, an increase in α from 0.5 to 2 corresponds to a decrease of forest potential evaporation of about 50%.

The canopy resistance (r_c)has been calculated for different types of crops as a ratio between minimal stomatal resistance (r_l) and leaf area index (I_{LA}). In our analyses r_l has been set at 100 s/m for grass, 350 s/m for forest, and 50 s/m for crop (e.g., Allen et al., 1998; Rana et al., 1994; Mascart et al., 1991; Pinty et al., 1989). The I_{LA} for different kinds of land

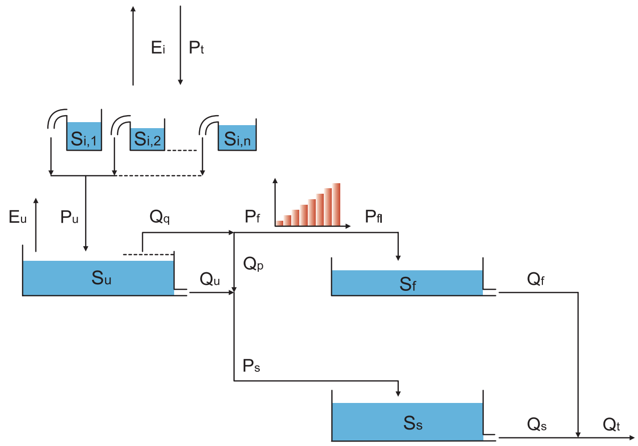

Fig. 4. Schematic representation of the FLEX model.

Table 1. Interception threshold varies between $I_{\max}$ and $I_{\min}$.

Land-use	$I_{\max}$ (mm)	$I_{\min}$ (mm)
Urban	1	1
Pasture	2	2
Agriculture	3	1
Deciduous	3	1
Coniferous	3	3

cover has been assumed to vary seasonally, as described in Gurtz et al. (1999). The values of r_l mainly depend on the plant type. However, a great variability is reported in the literature. Noilhan and Mahfouf (1996) report that r_l can be of the order of 40 s/m for a closed live crop canopy, and reach values up to 500 s/m when plants experience maturation or senescence.

The aerodynamic resistance has been estimated as a function of wind speed and roughness lengths governing momentum transfer and transfer of heat and vapour. For the forest the wind speed measured at meteorological stations has been transformed into the wind speed above the forest. Roughness lengths for different types of vegetation have been estimated from crop height (Allen et al., 1998) and from the plant area index as described by Shaw and Pereira (1982).

The energy available for transpiration ($E_{u,p}$) has been calculated subtracting from the potential evaporation the energy consumed in the interception process (see Table 3). The potential transpiration for the entire catchment was calculated averaging the contributions of different land-uses according to their proportion within the catchment.

The model was run at a daily time step, using daily data of precipitation, discharge (measured at Borgharen) and meteorological variables as described in Sect. 2. The evaluation period is between the years 1911 until 2000. The proportions of land uses, and in particular the fractions occupied by deciduous and coniferous forest, were considered variable within

Table 2. Description of the Penman-Monteith Equation.

Penman Monteith Equation		
$E_p = \frac{1}{\lambda\rho_w}\frac{sR_n + c_p\rho_a(e_a - e_d)/r_a}{s + \gamma(1+\alpha r_c/r_a)}$		
Parameter	Description	Units
E_p	Potential evaporation	m/s
λ	Latent heat coefficient	J/kg
ρ_w	Density of water	kg/m^3
R_n	Net radiation	W/m^2
s	Slope of the temperature-saturation vapour pressure curve	kPa/K
c_p	Specific heat of air at constant pressure	J/(kg K)
ρ_a	Density of air	kg/m^3
e_d	Actual vapour pressure of the air	kPa
e_a	Saturation vapour pressure for the air temperature	kPa
γ	Psychrometric constant	kPa/K
r_a	Aerodynamic resistance	s/m
r_c	(Bulk) surface resistance	s/m
α	Stomatal resistance coefficient	–

Table 3. Schematic description of model equations.

Equations	Notes
$P_{u,k} = \begin{cases} P_t & \text{if } S_{i,k} = I_{max,k} \\ 0 & \text{if } S_{i,k} < I_{max,k} \end{cases}$	k: land-use index
$E_{i,k} = \begin{cases} E_{i,p} & \text{if } S_{i,k} > 0 \\ 0 & \text{if } S_{i,k} = 0 \end{cases}$	
$P_u = \sum_k (w_k P_{u,k})$	w_k: land-use fraction
$E_i = \sum_k (w_k E_{i,k})$	
$C_r = \frac{1}{1+exp\left(\frac{-S_u/S_{fc}-1/2}{\beta}\right)}$	C_r: runoff coefficient
	S_u: UR storage
$Q_q = C_r P_u$	
$Q_p = Q_q D$	
$P_f = Q_q - Q_p$	
$Q_u = P_{\max}(S_u/S_{fc})$	
$P_s = Q_u + Q_p$	
$E_{u,p} = max(0, E_p - E_i)$	
$E_u = E_{u,p} \cdot min\left(1, \frac{S_u}{L_p S_{fc}}\right)$	
$Q_f = S_f/K_f$	S_f: FR storage
$Q_s = S_s/K_s$	S_s: SR storage

the period as done by (Ashagrie et al., 2006). This has an impact in the calculation of total evaporation.

3.2 Model evaluation

The model evaluation framework is based on the Dynamic Identification Analysis (DYNIA) introduced by Wagener et al. (2003). This approach is based on the GLUE (Generalized Likelihood Uncertainty Estimation) framework of Beven and Binley (1992), and it differs from it in the fact that the model, instead of being evaluated simultaneously over the entire observation record, is evaluated on a moving time window.

The approach consists of the following steps. First a uniform exploration of the parameter space is performed. For this purpose we used the Latin hypercube sampling technique on a predefined parameter range. Each parameter set corresponds to a model generation for which a measure of performance can be calculated. In this case we used the Nash and Sutcliffe efficiency measure (Nash and Sutcliffe, 1970). The performance is calculated on a moving time window. We divided the observation record in periods of four years, and calculated the model performance in each of them. Following the GLUE approach (Beven and Binley, 1992), for each time window we retained the best performing models as behavioural, and discarded the others. In the present case we retained the top 20% parameter sets. For each time window the performance of the behavioural parameter sets is rescaled to produce a cumulative sum of one. The rescaled performance can be used to build a cumulative distribution function of each parameter in each time window. This function can be used to determine various statistics, such as median and quantiles of model parameters.

The original purpose of the approach is to identify periods of identifiability for individual parameters and gain understanding on the information content of the data. In this case, we used this approach to determine trends in the model parameters, and possibly relate them to structural catchment modifications, such as land-use change.

Table 4. FLEX model parameters and corresponding units.

Parameter	Units	Definition	Range
C_i	–	Interception factor	0–5
S_{fc}	mm	Maximum UR storage	200–600
L_p	–	Moisture stress factor	0.5–1
β	–	Shape parameter of runoff generation	0.02–0.15
D	–	Runoff partition coefficient	0–0.4
$P_{\max}$	mm/d	Maximum percolation rate	0.1–0.9
N_{lagf}	d	Lag-time of FR transfer function	1.5–4
K_f	d	FR time scale	2–10
K_s	d	SR time scale	10–100

4 Results

The FLEX model in its present configuration is characterized by 10 parameters. Feasible ranges for these parameters are reported in Table 4, and have been determined through previous exploration of a wider parameter space. Initially, the model was evaluated by varying all parameters within their feasible range, subsequently the number of free parameters that were allowed to compensate for the modelling error has been reduced stepwise.

At first the parameter space was explored with 40 000 parameter sets which have been generated through the Latin hypercube technique. All 10 model parameters were allowed to vary. Results of the model evaluation approach are shown in Figs. 5 to 7. Figure 5 shows the trend in model parameters as calculated by the DYNIA approach. The continuous lines represent the median of the parameters, while the dashed lines represent the 20% and 80% quantiles. Although the model has a large number of parameters which can compensate for each other due to parameter correlation, it is possible to recognize a trend in some of the model parameters. The clearest trend is displayed by the parameter N_{lagf}, which represents the time to peak of the basin. It is possible to see that this parameter shows a continuously decreasing trend, which indicates that the catchment response has become progressively faster with time. This may be due to the progressive urbanization in the catchment, and in particular to the construction of roads and sewer systems which cause the flow to propagate at a much faster rate. Other causes may lie in the improved drainage from agricultural fields and river training works. Overall, the time to peak of the basin appears to have reduced by about one day, decreasing from an average of 3.5 to an average of 2.5 days.

In order to confirm this result, we performed an independent analysis evaluating the cross-correlation of the rainfall and discharge time series. This was calculated over a moving window of one year, during the all observation period. Results are shown in Fig. 6, which confirms that the optimal time lag between the two time series decreases with time, and that the distribution of time lags becomes more concentrated towards lower values.

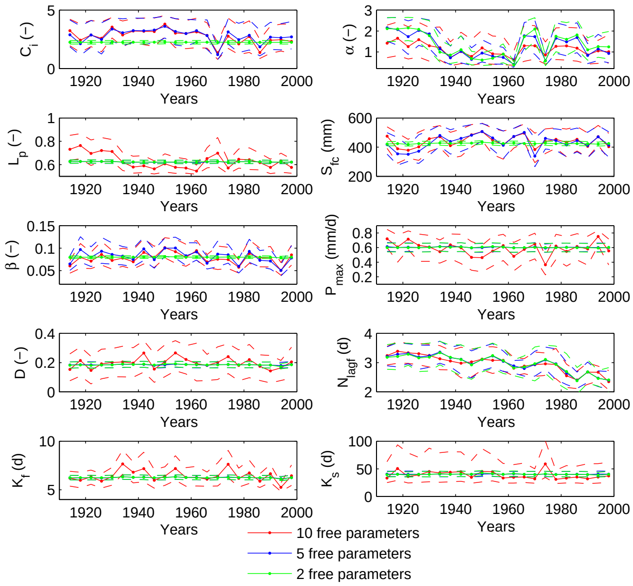

Fig. 5. Temporal trends of model parameters. The continuous line indicates the median, and the dashed lines indicate the 20% and 80% quantiles of the parameter distributions. Different colours indicate different number of "free" parameters.

Due to parameter correlation, the temporal trends of model parameters may be difficult to identify. Moreover, it may not be realistic to allow the variation of all model parameters. Hence we performed a parameter search constraining some model parameters to vary over a much smaller range (Fig. 5). This range was selected based on expert knowledge (C_i was fixed at 2) or at their average values (all other parameters). This also allows evaluating whether the modelling error can be corrected through a smaller number of free parameters. At first we allowed 5 parameters to vary, namely C_i, α, S_{fc}, β, and N_{lagf} (sampling the parameter space with 20 000 parameter sets). Finally only the two parameters α and N_{lagf} were left to vary (10 000 parameter samples).

The results of the model simulations are represented in Fig. 7. The dark line represents the observations, the grey line represents the optimal model with fixed parameters,

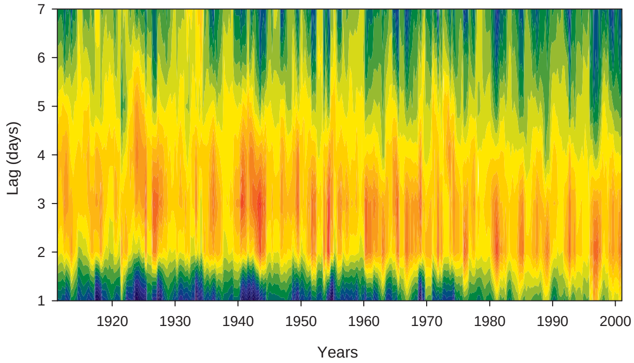

Fig. 6. Cross-correlation of rainfall and discharge time series, showing a decreasing trend in the time lag of the basin.

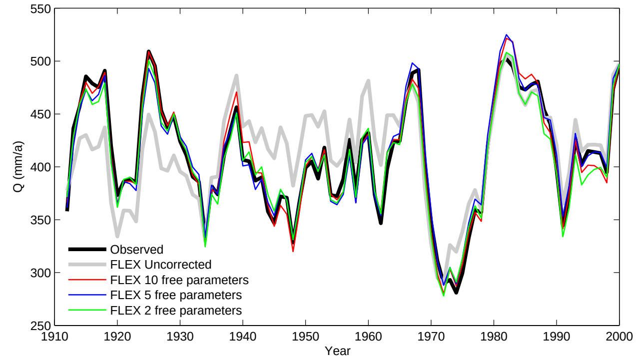

Fig. 7. Observed (black line) and simulated model discharge assuming fixed (grey line) and variable (coloured lines) parameter values.

similar to Ashagrie et al. (2006). The coloured lines represent the optimal performance when parameter sets are allowed to vary over time. We can see that time varying parameters can correct most of the modelling error. Moreover, the number of free parameters does not affect model performance. In fact, similar performance can be obtained by varying 10, 5 or 2 parameters.

This demonstrates that there is large equifinality between parameter sets, meaning that many combinations of parameters can compensate for the same effect. In particular, the parameters associated with the evaporation routine try to compensate for the error in the water balance (e.g. L_p and S_{fc}, which respectively determine the effect of moisture stress on transpiration and the maximum amount of soil moisture). However, it is not very likely that these parameters changed over time. Fixing these parameters forces the modelling error to be compensated by the parameters α , which affects the stomatal resistance and N_{lagf} for the lag time. If we do that, we can observe that the trend on the parameter α becomes clearer, and the uncertainty bounds become narrower, as less parameters are allowed to vary. The trend on the parameter N_{lagf} remains the same under this operation, which shows that this parameter is not correlated to this process. This is not surprising when looking at the model structure configuration. It is in fact the only model parameter that directly controls the lag time of the system. The outlier that can be observed in most parameters (e.g. α, K_s, C_i) occurs in the mid 1970s. This outlier is due to the year 1976 which was extremely dry, with a total precipitation of less than 400 mm/a. We believe that this year may be associated with events that are not taken into consideration by the model, such as different use of water or data errors. However, it may also contradict one of the main hypothesis of this study, which is that model parameters represent catchment characteristics, and are independent on climate.

The choice of parameters to fix depends on the hypothesis used and hence on an a-priory decision on which catchment characteristics are allowed to vary over time or to be maintained constant. Our knowledge about land-use change in the study area suggests that it is reasonable to assume that the time of concentration of the basin has changed during the period of observation, for reasons of urbanization and improved drainage. This supports the hypothesis that N_{lagf} should be considered as a variable parameter. Our knowledge about the change in forest management suggests that forest age may have varied during the period of observation, which supports the hypothesis that α should be allowed to vary over time. Assuming variability of other parameters is more difficult to justify. However, it is possible that other events outside our knowledge may have taken place.

Figure 8 represents the actual evaporation simulated by the model with fixed parameter values and by the model where parameters α and N_{lagf} were allowed to vary. The difference between the two models demonstrates the variability in evaporation due to forest management.

5 Discussion

The effect of land-use change has been extensively investigated in the literature. Various approaches have been introduced, including paired catchment experiments and modelling studies. When dealing with large catchments the most widespread approach is based on the interpretation of model results. In contrast to existing modelling studies which require information on the development of land-use practices over time, in this study we used a fully top-down approach that does not require preliminary information on land-use change. Our purpose is to identify temporal trends in model parameters which can be related to hypotheses of land-use change.

As a result of our approach, we have determined a significant decreasing trend in the time of concentration of the catchment. We hypothesize that this is due to urbanization, improved field drainage and river training. The construction of roads, sewer systems, the extension of impervious areas, and the improved drainage from agricultural fields are some of the causes that may have reduced the lag time of the catchment.

This result is relevant in relation to previous study on this area. While Tu Min et al. (2005) attributed the increase of flood frequency primarily to climate change, the decrease of concentration time of the catchment suggests that land-use change may also have contributed to this effect.

A second and more complex outcome of this study relates to the closure of the water balance of the catchment. In contrast to the lag time of the system, which is influenced by a single model parameter, the catchment water balance is influenced by a large number of parameters, which results into equifinality. Hence, a number of causes may be responsible for the anomaly in the rainfall-runoff relation identified by Ashagrie et al. (2006).

Historical reconstruction of land-use change within the catchment area has indicated a gradual shift of the total forested area (roughly constant throughout the observation period) from deciduous to coniferous forest (DGRNE, 2000). Moreover, Petit and Lambin (2002) have shown that the rate of land-use change was maximum between the years 1923 and 1957, which corresponds to the period of the anomaly.

Land-use change due to reforestation is likely related to the different use of forest areas during the last century. Industrial development, mining and the growth of population led to an increase in European consumption of wood and wood products. The total consumption of wood rose from 270 to 340 million cubic meters in the period from 1910 to 1960 (FAO, 1964). During the Second World War, similar to other resources, forests were overexploited (Pearson, 2006). After the Second World War, afforestation activities in Europe grew to a high level, which slowed down during the last two decades of the 20th century (Dirkse and Daamen, 2004). Efforts were made to improve both forest productivity and resource conservation.

As a result of the different practices of forest exploitation, during the last decades of the 20th century the average forest age had a tendency to increase. Dirkse and Daamen (2004) state that in the Netherlands, due to changes in forest management (less clear cut and more thinning), between years 1980 and 2001 the average age of trees in standing forests increased by 10 years (from 43.3 to 53.3 years).

The relation between stand age and evaporation in different types of trees and climates is still under investigation. However there is an increasing body of evidence that demonstrates that a young forest evaporates considerably more than mature forest. Kuczera (1987) developed an idealized curve for mountain ash forest that relates annual water yield to stand age. Similar curves were obtained by Shiklomanov and Krestovsky (1988) for 33 types of forest of the northern-east part of Russia. After these pioneering works, several other studies followed, showing evidence of decline in evaporation rates with tree age (Scott and Lesch, 1997; Watson, 1999; Vertessy et al., 2001; Delzon and Loustau, 2005; Farley et al., 2005).

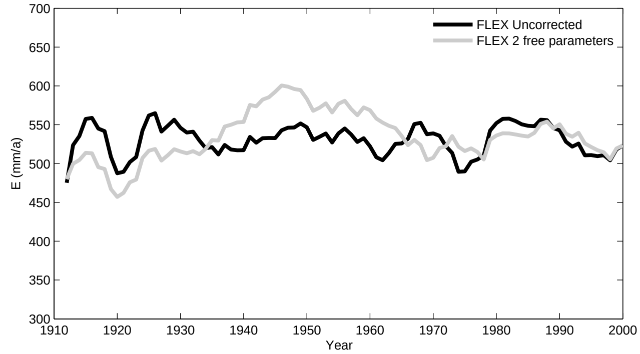

Fig. 8. Actual evaporation rates simulated by the FLEX model with fixed parameters, and by the FLEX model where parameters α and N_{lagf} were allowed to vary.

Although results are difficult to generalize to different climates and forest types, forest age appears to significantly affect the catchment water balance. Vertessy et al. (2001) estimated that annual overstory transpiration declines by 66% when tree age increases from 15 to 240 years. Scott and Lesch (1997) determined that the afforestation of a catchment with an average runoff of 236 mm/a caused the stream to dry up completely after 12 years. Brown et al. (2005) reviews different paired catchment experiments that were used to assess the impact of afforestation on water yield.

In the Meuse catchment, it is reasonable to hypothesize that the average age of the forest stands has varied over time. In our modeling exercise, this reflects into allowing for time variability of the parameter α which scales the canopy resistance from young to mature forest. The temporal trend of the parameter α shows that it is consistently higher than 1 in the initial period of the century, lower than 1 in the years 1930–1965, and around 1 in the last part of the observation period (corresponding to mature forest). Based on the model hypotheses, this is interpreted as a forest that evaporates more intensively during the middle part of the century than at the beginning or at the end of the observation period.

It is important to notice that the values of the parameter α correspond to plausible ranges according to the literature. Depending on the range of this parameter, the forest potential evaporation varies between + or −20%, which is consistent with field experiments at several locations (e.g. Vertessy et al., 2001).

The hypothesis of variable forest age explains the anomaly in the rainfall-runoff behavior as it allows a closure of the catchment water balance. However, we are aware of the limitations of our study, which partly derive from the intrinsic limitations of the available data during the period of investigation. Hence further research is needed to confirm or reject the hypothesis on the evaporative demand of growing forest. A possibility is to collect and interpret data from historical archives, which can provide information on wood production and wood consumption during the study period.

In addition, it should be noted that other catchment structural changes may be responsible for the observed anomaly. In 1923 a program to improve the navigation in the Meuse began, which involved reorganization of locks, channel bed regulation, and building of hydroelectric power stations. Simultaneously, a campaign to remove islands of the Meuse, which constituted obstacles to the flow of water, was launched (Nienhuis, 2008). Also war damage reconstruction came to an end (with increased net water consumption from various heavy industrial plants). These historical factors imply considerable and complex changes in water circulation and consumption in the basin.

6 Conclusions

The purpose of this study was to analyse the effect of structural changes on the discharge of the Meuse basin during the past century. As little quantitative information is available over this extended period, we assumed a fully top-down approach which does not require prior information on land-use. The approach is based on a dynamic evaluation of a hydrological model and on the consequent interpretation of the temporal trends obtained in model parameters.

Our results show that the time of concentration of the catchment has significantly reduced during the observation period. We think that this may be due to urbanization, improved field drainage and river training. A second result relates to the hypothesis that variable forest age may have significantly affected transpiration and consequently the water balance of the catchment. We show that this is a plausible hypothesis according to the literature and to our knowledge of the study area.

The Meuse basin has been subject to several studies that investigated the reasons of the observed change in rainfall-runoff behaviour. Whereas previous studies concluded that this change is due to climate change rather than to land-use change, our investigation indicate that land-use and land management changes are likely causes for observed changes in the hydrological behaviour of the Meuse river basin.

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