Hydrological drought analysis in the Hupsel basin using different physically-based models

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Abstract Three different physically-based models were applied to the Hupsel basin to explore their potential to simulate hydrological droughts. The models include water balance models with a simple (BILAN) or a detailed description of the evapotranspiration process (HBVMOR) and a groundwater and surface water flow model (MOGROW). Onset, duration and deficit volume of drought events were derived from observed and simulated hydrographs for the period 1980-1983. Onset of the major drought, i.e. 1982 was well predicted with HBVMOR and MOGROW, whereas BILAN has some limitations because of the monthly time step. Duration and deficit volume of the 1982 drought were underestimated by all models (10–30%). HBVMOR performs best when all droughts events were considered (differences: 15–20%). The strength of the physically-based models lies within their possibility to explore the impact of man-induced changes on droughts, but they still need some improvement if a very accurate simulation of low flows and associated droughts is required.

INTRODUCTION

Droughts seriously affect water resources and may have a detrimental impact on environment and nature reserves. This study focuses on hydrological droughts in terms of streamflow deficits. Hydrological droughts are defined as periods during which the streamflow is below a certain threshold level. Daily and monthly streamflow series were used to assess drought duration and deficit volume derived from both measured and simulated streamflow. In the framework of the FRIEND Low Flow Group two key approaches are being used, i.e. statistical modelling and physical-based modelling, which are complementary. Physically-based models were introduced: (a) to understand the underlying hydrological processes of streamflow generation in a basin more thoroughly, and (b) to simulate streamflow data for hypothetical hydrological conditions, allowing an impact assessment (e.g. change in land use or climate, or groundwater abstraction). Three different physically-based models were applied by the Low Flow Group to simulate streamflow time series and subsequently to analyse droughts. These were the BILAN, HBVMOR and MOGROW, which are using widely different concepts due to different objectives, basin characteristics and data availability. The purpose of this paper is to explore the
reliability of the models by comparing the simulated droughts with each model for the Hupsel basin in The Netherlands. Elsewhere the impact of human activities on hydrological droughts simulated with these models is presented (Querner et al., 1997).

METHODS AND MATERIALS

Hupsel basin

The Hupsel experimental basin (6.5 km²) is situated in the east of The Netherlands close to the German border (Warmerdam et al., 1982). The basin is relatively flat, its altitude varies between 24 and 33 m a.m.s.l. The average slope of the area is about 0.8%. Agricultural land use dominates in the basin, i.e. 70% grassland, 21% arable land (mainly maize) and 6% forest. Pleistocene eolian, fluviatile or glacial deposits, which usually consist of sand with some gravel, cover Tertiary, marine clays. This clay is found at a depth of 1 m in the east and dips to the west, where the top is at 8 m below soil surface. The Pleistocene sediments form a small unconfined aquifer with relatively shallow water tables. The aquifer transmissivity varies between 10 to 350 m² day⁻¹. The basin has a dense surface water network. The average annual precipitation is about 770 mm. Daily discharge data from 1969 to 1992 were available. The average discharge is 273 mm.

Models

BILAN (“Balance” in Czech) is a water budget model, which was developed to assess the water balance components of a basin in monthly time steps. It is a single-cell model, where the entire basin is represented as one cell (Kasprárek & Krejčová, 1994). The model aims at the evaluation of long time-series. BILAN has been developed both for mountainous and lowland groundwater basins. The hydrological processes, such as evapotranspiration, the generation of surface runoff or baseflow, are represented by a set of empirical relationships. The model uses average basin rainfall, air temperature and relative air humidity as input data, and produces monthly data of basin evapotranspiration and streamflow (total of surface runoff, interflow and baseflow). Furthermore, average water storage in the snow cover, the unsaturated and saturated zone are separately simulated. The model is calibrated with an optimization technique. Therefore measured streamflow data series are a prerequisite.

HBVMOR is a single-cell water budget model too, but with a time step ranging from 1 to 24 h depending on the evapotranspiration process to be simulated (Tallaksen, 1993). It was developed for a detailed analysis of basin behaviour and associated streamflow, and it includes a comprehensive description of evapotranspiration. HBVMOR consists of a physically-based evapotranspiration sub-model and a conceptual rainfall–runoff sub-model. It combines the HBV model, which means Swedish Hydrometeorological Institute, and AutoMORecs, where AUTO stands for automatic climate stations in Norway and MORECS for the Meteorological Office (Great Britain) Rainfall and Evaporation Calculation System.
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The model includes algorithms for snow accumulation and melting, interception and transpiration, capillary rise, and runoff generation. Some principles of distributed models are included, such as separate altitude zones for the simulation of snow accumulation and melting (semi-distributed model). The model requires hourly meteorological data to compute potential evapotranspiration and interception. Parameters of the rainfall–runoff sub-model are obtained by calibration against daily time series of observed streamflow. The model output consists of daily data of interception, actual evapotranspiration, streamflow and the water content of the various reservoirs.

MOGROW (Modelling GROundwater flow and flow in surface Water systems) combines the simulation of unsaturated–saturated groundwater flow and water flow in a surface water system (Querner, 1997). It is a regional model; the region or basin is divided in triangular cells for the simulation of subsurface flow. The surface water courses, including special structures (e.g. weirs), are incorporated in a nodal network to simulate surface water flow. The distinction of cells allows the specification of a complex geometry of the basin and surface water system, and spatially varying characteristics, e.g. land use, physical properties of soils, transmissivities of the aquifers and hydraulic resistances of the aquitards. So, regional heterogeneity represented by point data can be incorporated by using different input data for each cell. A water budget rise is used for the root zone, whereas the flow equations are solved for the unsaturated subsoil, the saturated system and the surface water system. In this study a time step of 1 day was used for the specification of the time-dependent input data, such as precipitation and potential evapotranspiration. For the simulation of surface water flow a time step of half an hour was used. The output comprises daily data of actual evapotranspiration, soil moisture storage, groundwater heads in the aquifers for each cell, and streamflow for each river network section. The model is used for a detailed analysis of (sub-)basin behaviour and streamflow generation, usually for a number of years. MOGROW is developed for lowland groundwater basins, and does not account for snow or hillslope hydrology. Although the model can be run without calibrating because parameters have a physical meaning, generally a restricted calibration is carried out using observed groundwater heads and streamflow records.

The parameters of the BILAN model were optimized using data from the Hupsel experimental basin over the years 1976–1983. Average daily discharge was obtained for the BILAN model by dividing simulated monthly mean values by the number of days per month. HBVMOR was calibrated with data from 1980–1981, and validated with data from 1982–1983. Some parameters of the MOGROW model were fine-tuned with data from 1981 (e.g. parameters accounting for preferential flow in the unsaturated zone). A validation was carried out with data from 1982–1985. Then MOGROW was applied to the period 1969–1992. All three models have the years 1980–1983 in common. Measured and simulated time series of streamflow data from these 4 years were used in this study to identify droughts and to compare the models.

Drought identification

The droughts events were obtained from the measured and simulated streamflow
hydrograph by considering flow situations where the daily discharge is below a certain threshold level (low flow spells). The 70th percentile of the flow duration curve ($Q_{70}$) of the measured streamflow was used as a threshold level, i.e. the streamflow which is exceeded in 70% of the days. Each drought event is characterized by its onset, duration (length of the low flow spell) and deficit volume (sum of daily deficits within a low flow spell). Partial duration series (PDS) of drought duration and deficit volume were preferred in this study instead of annual maximum series because of the relatively short common simulated time series available. This implies that all drought events during a year irrespective of the severity are considered. Mutually dependent droughts were pooled into single drought events for the models HBVMOR and MOGROW which use a daily time step by applying the Moving Average (MA) procedure as proposed by Tallaksen et al. (1997) for the PDS approach. An averaging time interval of 10 days was used (MA = 10 days). All processing of the streamflow data was done by the software code EXDEV (Ričica & Novicky, 1995).

RESULTS

Observed and simulated streamflow

The observed and simulated daily streamflow data were converted to flow duration curves (FDC) to explore the nature of the basin and to evaluate model performance (Fig. 1). Because of the relatively thin aquifer, shallow water tables and dense surface water network, the streamflow of the Hupsel basin has a flashy nature resulting in a steep flow duration curve. In dry years the basin suffers from summer

![Flow duration curves derived from measured and simulated data from the Hupsel basin for the period 1980-1983.](image)
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Droughts, sometimes resulting in a completely drying up of the brook (<5% of the days). The $Q_{70}$ derived from the 1980–1983 dataset equals 0.007 m$^3$ s$^{-1}$ (indicated as $Q_{70}^{sh}$; sh: period 1980–1983). The flow duration curve was also computed for the observed dataset from 1969–1992, which resulted in a $Q_{70}$ of 0.016 m$^3$ s$^{-1}$ ($Q_{70}^{lo}$; lo: period 1969–1992). In the low flow range (flow with a probability exceedance of less than 30%), the 1980–1983 period was slightly dryer than the 1969–1992 period. Both $Q_{70}$s were used in the following drought analysis.

The FDCs derived from the simulated hydrographs show that the BILAN model produced a more flat curve than the observed one, which implies an underestimation of the peak flows and an overestimation of the low flows. This is typical for a model using a monthly time step. The deviation between the FDCs from BILAN and the observed data, however, is small. The FDC derived from the HBVMOR model shows a better agreement with the observed one than the FDC based upon the MOGROW simulation. Especially, in the low flow range the MOGROW model simulates slightly higher streamflows than observed. These differences are caused by MOGROW parameters, which were not thoroughly calibrated by comparing measured and simulated streamflow as was done by the optimization procedure of BILAN and HBVMOR.

Simulation of drought characteristics

In the 1980–1983 period 10 drought events were identified based upon the observed hydrograph and the $Q_{70}^{sh}$. The 1982 drought is the most severe one. The probability distributions derived from the 1969–1992 dataset indicate that the 1982 drought has an exceedance probability of about 5% both in terms of duration and deficit volume.

**Drought onset** The 1982 drought started on 11 July and 16 May for the $Q_{70}^{sh}$ and $Q_{70}^{lo}$ thresholds, respectively (Table 1). The estimated onset with MOGROW deviates 12 and 2 days, and with HBVMOR the difference equals 2 and 15 days. BILAN estimates the onset well for the $Q_{70}^{sh}$ threshold (difference of 10 days). However, in case of the $Q_{70}^{lo}$, BILAN was unable to predict the onset adequately (difference >1 month). The monthly time step as used in BILAN prevents an accurate prediction of the onset.

**Drought duration** The 1982 drought lasted 127 and 186 days for the $Q_{70}^{sh}$ and $Q_{70}^{lo}$ threshold level, respectively (Fig. 2(a) and (b)). All three models underestimate these durations. Dependent on the selected threshold level, the underestimation using

<table>
<thead>
<tr>
<th>Threshold $Q_{70}$ (m$^3$ s$^{-1}$)</th>
<th>Onset: Measured</th>
<th>Models: BILAN</th>
<th>HBVMOR</th>
<th>MOGROW</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.007 ($Q_{70}^{sh}$)</td>
<td>11 July 1982</td>
<td>1 July 1982</td>
<td>13 July 1982</td>
<td>29 June 1982</td>
</tr>
<tr>
<td>0.016 ($Q_{70}^{lo}$)</td>
<td>16 May 1982</td>
<td>1 July 1982</td>
<td>31 May 1982</td>
<td>14 May 1982</td>
</tr>
</tbody>
</table>
BILAN equals 3 and 34%. For HBVMOR and MOGROW these deviations are 25 and 30%, and 21 and 11%.

The estimation of the duration for all drought events improves when using the $Q_{70}^{th}$ threshold level. The HBVMOR model shows the best agreement with the drought durations derived from the observed hydrograph. BILAN and MOGROW are unable to adequately predict the durations of the events 2, 3, 4 and 5 for the $Q_{70}^{th}$ (Fig. 2(a)) and the minor drought events 5 and 6 for the $Q_{70}^{lo}$ (Fig. 2(b)). The average percentage of the absolute difference between the observed and the HBVMOR simulated drought durations for the three most severe droughts deviates 20% as the $Q_{70}^{th}$ threshold level is used. This percentage equals 19% for the four most severe droughts in case of using the $Q_{70}^{th}$ threshold. The average percentages

![Graphs showing drought durations and deficit volumes](image)

**Fig. 2** Drought durations and deficit volumes for two threshold values ($Q_{70}^{th}$ and $Q_{70}^{lo}$) derived from measured and simulated data from the Hupsel basin for the period 1980–1983.
for BILAN (25 and 22%) and MOGROW (50 and 18%) are higher, especially for the $Q_{70}^{th}$ threshold.

**Deficit volumes** The deficit volume of the 1982 drought was 50,241 and 187,583 m$^3$ for the $Q_{70}^{th}$ and $Q_{70}^{th}$ threshold levels, respectively (Fig. 2(c) and (d)). Similar to the duration, all three models underestimate these deficit volumes. BILAN underestimates the deficit volumes of the 1982 drought by 20 and 28% dependent on the threshold level. For HBVMOR and MOGROW the underestimations are 21 and 32%, and 6 and 16%.

In general HBVMOR estimates deficit volumes best. Using $Q_{70}^{th}$ as threshold level the average percentage of the absolute difference of the first three drought events (Fig. 2(c)) equals 18%. For the $Q_{70}^{th}$ this percentage of the first four drought events (Fig. 2(d)) is 16%. For BILAN and MOGROW these percentages are substantially higher, i.e. 38 and 34%, and 53 and 43%, respectively.

**CONCLUSIONS**

The three physically-based models included in the study can reasonably well simulate the streamflow of the Hupsel basin in the period 1980-1983. In the low flow range the HBVMOR model shows the best agreement with the observed streamflow. All three models identify the major drought in the relatively short time series, i.e. the 1982 drought. The onset of the drought is well predicted with the more comprehensive models HBVMOR and MOGROW, which use a daily time step. The prediction of the onset with the BILAN model is not very accurate in some cases because of the monthly time step. The duration and the deficit volume of the 1982 drought is underestimated by all models. Differences up to about 30% prevail between droughts derived from simulated and observed hydrographs dependent on the model and the selected threshold level. When all drought events are considered, the drought duration and deficit volume simulated with HBVMOR show the best fit with the observed series. The average difference between observed and HBVMOR simulated droughts in terms of duration and volumes equals 15-20%. For BILAN and MOGROW the average differences are between 20 and 50%. HBVMOR performs better than BILAN because of the smaller time step. Furthermore the required parameter optimization of rainfall-runoff models (BILAN and HBVMOR) usually results in a better estimation of the streamflow than a more sophisticated model which simulates groundwater flow and surface water flow without a comprehensive calibration of model parameters (MOGROW). Performance of all models is better in case of a higher threshold level, i.e. the $Q_{70}$ of the period 1969-1992 gives better results than the $Q_{70}$ for the period 1980-1983. The drought assessment with BILAN would improve when droughts would be derived from average monthly observed streamflow instead from daily flows as in this study.

Irrespective of the complexity of some of the models, the reliability of simulating details of all droughts is limited.

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REFERENCES


