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Hydrological modelling of low flows for operational water resources management

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Abstract: Hydrological modelling of low flows is performed in this study for operational water resources management. The HBV hydrological model is used to simulate, reconstruct and extent the observed discharges to a complete 30-year daily simulated discharge dataset at Yermasoyia river, Cyprus. Calibration and validation techniques are used to assess the validity of the hydrological model for low flow modelling. Low flows simulated and observed characteristics are estimated and compared using the monthly varying threshold approach. Then, the monthly threshold method and the inter-event time and volume criterion (IC) is applied to derive independent sequences of low-flow events. Severity-duration-frequency (SDF) curves of low flows are developed based on the annual maximum severities for fixed durations at 30, 60, 90, 180 and 360 days. The best theoretical probability distribution is then selected for each threshold method based on individual probabilistic analysis, and finally the SDF curves for the study threshold are derived to quantify the relationship among the severities, durations, and frequencies. Hence, based on typical simulated drought characteristics (deficit volume and duration), this study develops quantitative relationships for low flows among drought parameters using monthly varying threshold levels.

Key words: hydrological droughts, low flows, hydrological modelling, low flow indices, severity–duration–frequency (SDF) curves, streamflow deficits, threshold level method

1. INTRODUCTION

Droughts are generally considered as periods with insufficient precipitation, soil moisture and water resources for sustaining and supplying the socio-economic activities of a region (Mishra and Singh, 2010). The American Meteorological Society (2004) adopted a four-type drought classification system based on the nature of the water deficit. According to this classification, meteorological, hydrological and agricultural droughts are considered environmental droughts, and they are defined as periods with insufficient amounts of precipitation, river flow or groundwater, and soil moisture, respectively. The fourth drought type is the socio-economic drought, which is related to the failure of water resources systems to meet the water demands. Droughts are long-term phenomena affecting large regions causing significant damages both in human lives and economic losses. Droughts are the costliest natural disaster of the world and affect more people than any other natural disaster (Wilhite, 2000). In the past few years, major drought events have been recorded in Ethiopia, Australia, United States, Eurasia, Middle East, and southern Europe (IPCC, 2012; AghaKouchak et al., 2013).

Streamflow drought properties have been extensively analysed for the design of hydrotechnical projects and water resources planning and management during the last two decades. Information on the magnitude and frequency of low flows is very important for streamflow drought analysis at operational level in public water supply systems. The objective of this study is to model hydrological droughts for operational water resources management. Hydrological droughts are estimated using rainfall-runoff models and low flow analysis techniques. It should be noted that a low flow event may not necessarily be a drought event. Low flows are usually seasonal-periodical events that are integral parts of the hydrograph, while droughts are caused by abnormal lack of precipitation and water resources (Tallaksen and van Lanen, 2004). The methodology is developed and demonstrated for volume deficits using probabilistic analysis on a semi-arid catchment in

Cyprus. The probabilistic analysis provides an overall characterization of the basin concerning the drought events and is oriented to long term drought management and infrastructure (i.e. reservoirs) design and operation.

2. STUDY AREA

The study basin is the Yermasoyia watershed, which is located on the southern side of mountain Troodos of Cyprus, roughly 5 km north of the city of Limassol. The watershed area is 157 km^2 and its elevation ranges from 70 m up to 1400 m. Most of the area is covered by typical Mediterranean-type forest and sparse vegetation. A reservoir with storage capacity of 13.6 hm^3 was constructed downstream of the mouth of the watershed in 1969 for irrigation and municipal water supply purposes (Hrissanthou, 2006). The climate of the area is of Mediterranean maritime climate, with mild winters and hot and dry summers. Precipitation is usually generated by frontal weather systems moving eastwards. Average basin-wide annual precipitation is 640 mm, ranging from 450 mm at the low elevations up to 850mm at the upper parts of the watershed. Mean annual runoff of the Yermasoyia River is about 150 mm, and 65% of it is generated by rainfall during winter months. The river is usually dry during summer months. The peak flows are observed in winter months and produced by rainfall events. Good-quality daily precipitation, maximum and minimum temperature for a period of 30 years (1969-1998) from Limassol meteorological station were used in this study. Potential evapotranspiration values are estimated with the Hargreaves equation (Hargreaves and Samani, 1985; Allen et al., 1998). Furthermore, 11 years of daily streamflow data (October 1986 – September 1997) were available for the Yermasoyia watershed. Further details of the Yermasoyia watershed could be found in recent studies (Hrissanthou, 2006; Loukas and Vasiliades, 2014).

3. METHODOLOGY

The objective of this study is to derive hydrological drought severity-duration-frequency (SDF) curves using low flows estimated from a rainfall-runoff model and analysed with the threshold level method. Low flow severity is defined as the total water deficit volume to the target threshold for a given drought duration. A conceptual rainfall-runoff model following the structure of the HBV model (Parajka et al., 2007) is used to reconstruct and extent the observed discharges to a complete 30-year daily simulated discharge dataset at Yermasoyia watershed.

In this study, a semi-distributed conceptual model, HBV, was chosen for hydrologic simulation of the rainfall runoff process. The motivation of choosing this particular model is that the model was used in previous studies and showed a good performance in this watershed (Paraskeuas et al., 2015). The model runs on daily values of precipitation, temperature and estimates of potential evapotranspiration. Flow observations are used for calibration and validation of the model. The model contains routines for snow accumulation and melt, soil moisture accounting, runoff generation and a routing procedure. The snowmelt routine of the HBV model is based on the degree-day approach. It is based on air temperature, with a water holding capacity of snow which delays runoff. The soil moisture routine of the model controls runoff formation, accounts for soil field capacity and change in soil moisture storage due to rainfall/snowmelt and evapotranspiration. The excess water from the soil moisture zone transforms to runoff in the response routing. The response function of the model consists of two reservoir – one upper nonlinear, one lower linear, and one transform function. The runoff is computed by adding the contribution from the upper and lower reservoir, and the generated runoff is routed through a transformation function in order to get a proper shape of the hydrograph at the outlet of the watershed.

The 15 parameters of the HBV model need to be calibrated in order to provide model output that closely resembles observed data as it is a conceptual model. In this study, the first 6 years of runoff data (from 1986 to 1992) were used to calibrate the hydrologic model and the last 5 years of data

(1992-1997) were used to validate the model. The Nash-Sutcliffe model efficiency on square root flows was used as the objective function of the optimisation process (Krause et al., 2005). The square root transformation of the flow values leads to the flattening of peaks and the low flows are kept more or less at the same level. As a result the influence of the low flow values is increased in comparison to the flood peaks resulting in an increase in sensitivity, similarly to the logarithmic transformation (Krause et al., 2005). The calibration of the model was performed automatically using the Self-Organising Migrating Algorithm (SOMA) optimisation algorithm (Zelinka, 2004). The SOMA is a general-purpose, stochastic optimisation algorithm. The approach is similar to that of genetic algorithms, although it is based on the idea of a series of migrations by a fixed set of individuals, rather than the development of successive generations. It can be applied to any cost-minimisation problem with a bounded parameter space, and is robust to local minima.

The HBV simulated discharges are then analysed with the monthly varying threshold level method in the estimation of derived streamflow deficits and durations. In monthly varying threshold, there are twelve different thresholds, one for each month. The threshold for January results from the values of flow of January for the entire period of record. The monthly 50th percentile values of the flow duration curve are selected as the threshold choices which are suitable for semiarid catchments where zero runoff occurs during summer months (Sarailidis et al., 2015). Then, the inter-event time and volume criterion (IC) is applied to derive independent sequences of low-flow events (Tallaksen et al., 1997). According to IC method two events are pooled if: (a) they occur less than a predefined number of days, t_{min}, apart (the inter-event time (τ_i) is less than t_{min}) and; (b) the ratio between the inter-event excess volume (s_i) and the preceding deficit volume, v_i, is less than a critical ratio, p_i. The adjacent deficits are then pooled if the aforementioned requirements are fulfilled. The pooled deficit characteristics (d_{pool}, d_i, d_{i+1} in days), (v_{pool}, v_i, v_{i+1} in mm) can be calculated as follows:

$$d_{pool} = d_i + d_{i+1} + \tau_i \tag{1}$$

$$v_{pool} = v_i + v_{i+1} - s_i \tag{2}$$

The IC method was tested on two Danish rivers with contrasting flow regimes and it was found that the optimal values of the pooling criteria were t_{min} = 5 days and p_i = 0.1 (Tallaksen et al., 1997). Sensitivity analysis is applied for accurate estimation of the method parameters. Finally, the HBV-simulated SDF curves are developed based on the annual maximum severities for fixed durations at 30, 60, 90, 180 and 360 days. Based on individual probabilistic analysis, the best theoretical probability distribution is selected and then the SDF curves are developed to quantify the relationship among the severities, durations, and frequencies or return periods. These curves also integrate the return period–duration curve to quantify the extent of the threshold method. Hence, this study developed quantitative relationships among drought parameters based on typical drought characteristics (deficit volume and duration) and monthly varying threshold levels.

4. APPLICATION AND RESULTS

4.1 Hydrological modelling of low flows

The methodology described above was applied to simulate flows at the outlet of the watershed using the HBV rainfall runoff model and to evaluate hydrological model accuracy. Three more evaluation metrics apart from the square root transformation of NSE (NSE($\sqrt{Q}$)) were employed for model evaluation: the runoff volume error (Vol. Error in %); the root mean square error between the simulated and the observed flow values (RMSE) and the Nash-Sutcliffe model efficiency (NSE). Table 1 presents the evaluation metrics for calibration and validation periods and for the complete period with the observed runoff data. Furthermore, Table 2 presents the comparison of the streamflow deficits for the observed and simulated flows for the period 1986-1997 (11 years). The observed and simulated streamflow deficits are calculated using the monthly varying threshold level method, according to which a deficit is defined as a period when the flow is below a predefined discharge (Yevjevich, 1967). In this study the IC pooling method was used in the observed and simulated flow timeseries. The IC method is preferred from other pooling methods since it produces more reliable results (WMO, 2008; Sarailidis et al., 2015). Default values as suggested were used in the IC method to eliminate the problem of having short duration drought events (Tallaksen et al., 1997). Deficit duration is defined as the period of time (d_i), when the flow is below the threshold. Deficit volume (v_i) is defined as the sum of discharges for the corresponding deficit duration, and deficit intensity (or severity) is defined as the ratio between the volume and the duration of deficit, and finally, the last characteristic is the minimum flow of a deficit. Based on Table 2 the HBV model is reproduce quite satisfactorily the observed runoff timeseries since the observed and modelled streamflow deficits have similar statistical characteristics. Hence, it could be used to extent and produce simulated streamflow series for the complete period of analysis 1969-1998.

Table 1. Evaluation metrics for assessing the accuracy of the HBV model

	NSE(√Q)	NSE	Vol. Error (%)	RMSE
Calibration Period (Oct 1986-Sep 1992)	0.92	0.87	-1.26	0.32
Validation Period (Oct 1992-Sep 1997)	0.89	0.82	-6.34	0.32
Complete Period (Oct 1986-Sep 1997)	0.91	0.86	-2.69	0.32

Table 2. Comparison of observed and simulated streamflow deficit characteristics for the period 1986-1997

Characteristic	Observed	HBV modelled
Number of drought events per year	3.55	3.48
Mean drought duration (d)	83.34	83.40
Mean drought deficit (mm)	26.77	23.89
Mean drought intensity (or severity) (mm/d)	0.24	0.22

4.2 Streamflow deficits analysis

The HBV simulated flow timeseries were used for hydrological drought modelling of low flows with the monthly varying threshold level method. The monthly 50th percentile values of the simulated flow duration curve are selected as the threshold choices which are suitable for semiarid catchments where zero runoff occurs during summer months. Then, the inter-event time and volume criterion (IC) is applied to derive independent sequences of low-flow events. Sensitivity analysis is applied for accurate estimation of the IC model parameters. Figure 1 presents the results of this analysis for IC model parameters ($3 \leq t_{min} \leq 15$ and $5 \leq p_i \leq 15$). Application of the sensitivity analysis showed that the inter-event time and volume criterion is an unbiased pooling method and there is no subjectivity in the choice neither of days of pooling nor of the ratio of volumes. This is reflected in Figure 1, where there is a good convergence of the different periods of days of pooling, and a good convergence of the three different ratios of pooling. The IC method with t_{min} =5 days and p_i=10% is selected to estimate the duration and the deficit volume or severity of the identified simulated drought events. Using the monthly varying threshold level method, deficits characteristics were derived for the monthly Q50 quantiles. Most streamflow deficits occur in winter months and in wet season (October-March) which is valuable information because deficits that occur in wet season are very important for water resources management in the study area (Fig. 2).

The knowledge of future volume of deficits is very important for the design of hydro-technical projects. In this study, a probabilistic analysis of maximum volumes of deficits was done for return periods 10, 20, 30, 50, 100, 250 and 500 years. In order to incorporate the influence of drought duration, annual maximum volumes were extracted for selected drought durations (30, 60, 90, 180, 360 days) for each hydrological year.

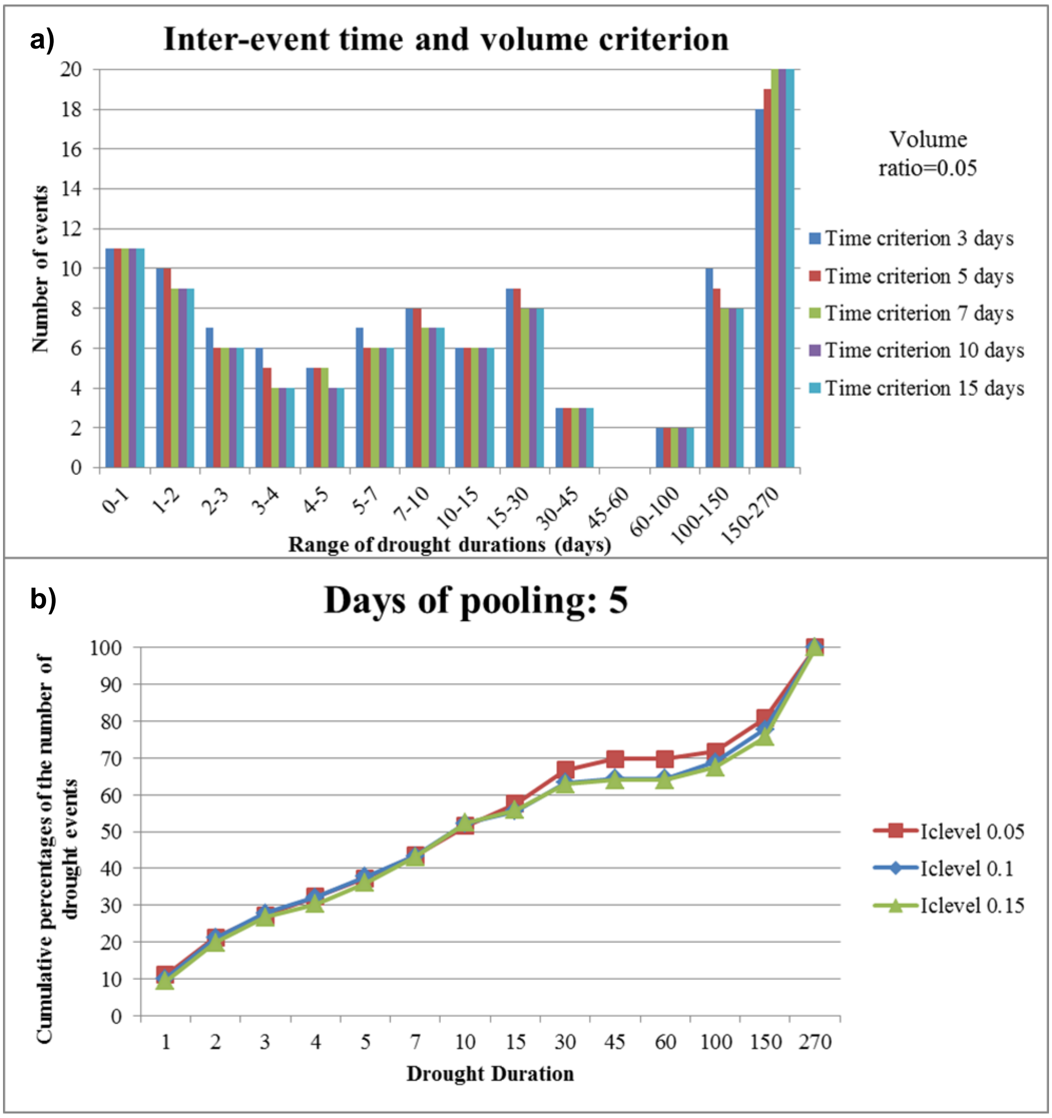

Figure 1. Sensitivity of the inter event time and volume criterion method: a) the effect of inter event time on low flow events and b) the effect of volume criterion on the estimated low flow events

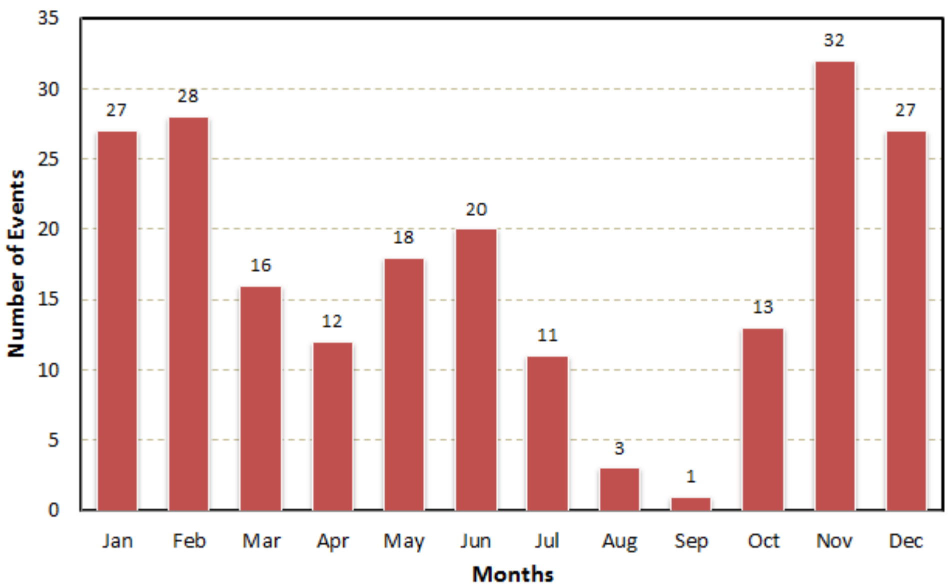

Figure 2. Estimated number of drought events for each month using the monthly varying threshold method

Several theoretical probability distributions were fitted to the extracted annual maximum volume deficits and the fitted theoretical distributions were evaluated with the use of Kolmogorov-Smirnov test. Results show that annual maximum volume deficits are best represented with the Pareto probability distribution (with L-moments estimated parameters) for the study durations. Figure 3a shows fitting of Pareto distribution to annual maximum volume deficits. Then, the Pareto distribution is used for estimation of volume deficits at typical return periods of 10, 20, 30, 50, 100, 250 and 500 years and the creation of volume deficit-duration-frequency curves, as shown in Figure 3b.

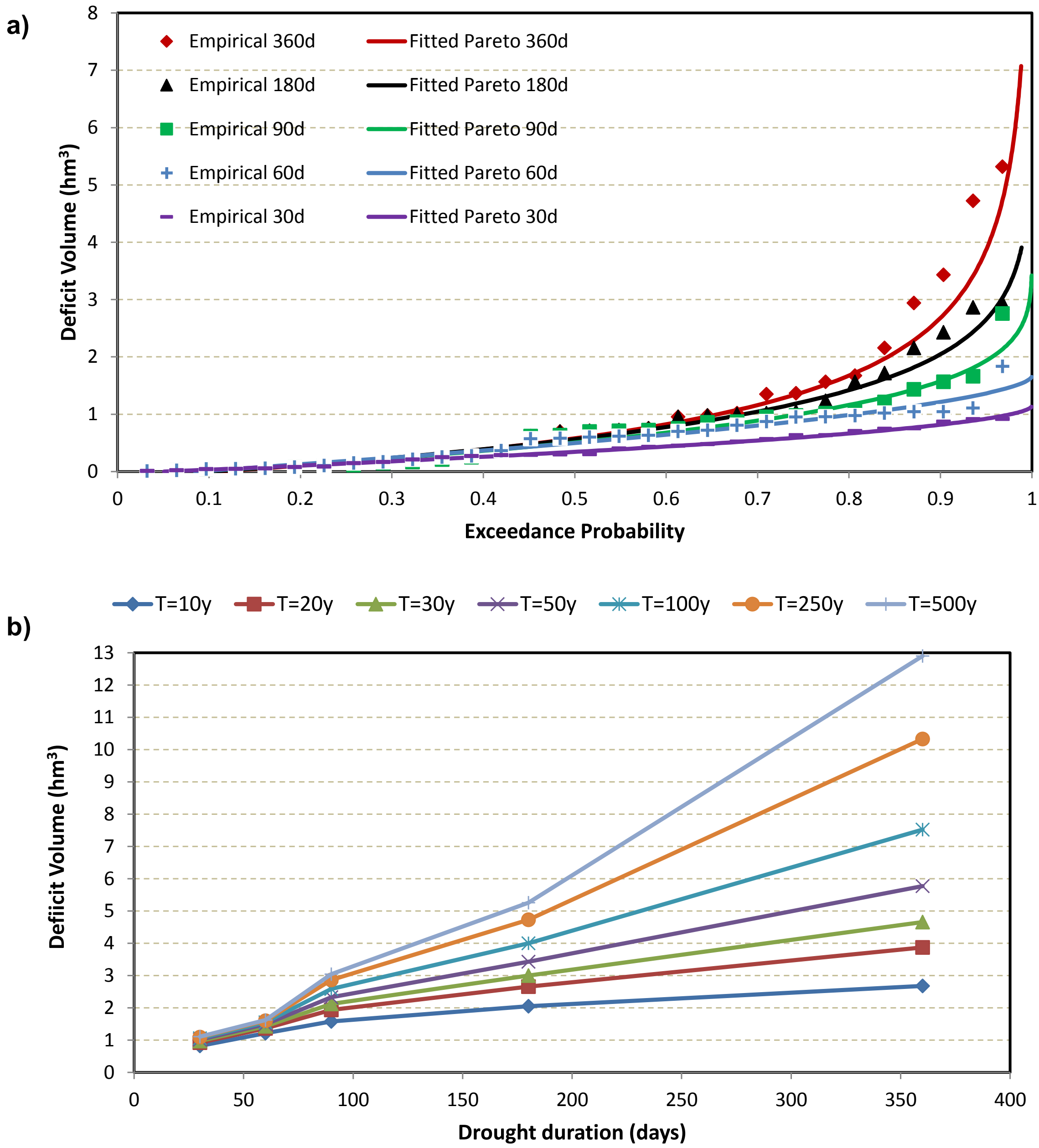

Figure 3. a) Fitting of Pareto theoretical distribution to annual maximum volume deficits for the study durations and b) Development of volume deficit-duration-frequency curves

5. CONCLUDING REMARKS

Hydrological modelling of low flows for operational water resources management is examined in this study. The HBV hydrological model is able to simulate accurately the observed low flow for the study watershed and it could be used as an operational tool to create synthetic discharge timeseries. Low flow events created with the use of the hydrological model and the monthly varying threshold approach are used to model streamflow characteristics. Severity-duration-frequency (SDF) curves of low flows are developed based on the annual maximum severities for fixed durations at 30, 60, 90, 180 and 360 days. Hence, based on typical simulated drought characteristics (deficit volume and duration), this study developed quantitative relationships for operational management of low flows.

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