Identification of appropriate temporal scales of dominant low flow indicators in the Main River, Germany

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Abstract Models incorporating the appropriate temporal scales of dominant indicators for low flows are assumed to perform better than models with arbitrary selected temporal scales. In this paper, we investigate appropriate temporal scales of dominant low flow indicators: precipitation (P), evapotranspiration (ET) and the standardized groundwater storage index (G). This analysis is done in the context of low flow forecasting with a lead time of 14 days in the Main River, a tributary of the Rhine River, located in Germany. Correlation coefficients (i.e. Pearson, Kendall and Spearman) are used to reveal the appropriate temporal scales of dominant low flow indicators at different time lags between low flows and indicators and different support scales of indicators. The results are presented for lag values and support scales, which result in correlation coefficients between low flows and dominant indicators falling into the maximum 10% percentile range. P has a maximum Spearman correlation coefficient (ρ) of 0.38 ($p = 0.95$) at a support scale of 336 days and a lag of zero days. ET has a maximum ρ of –0.60 ($p = 0.95$) at a support scale of 280 days and a lag of 56 days and G has a maximum ρ of 0.69 ($p = 0.95$) at a support scale of 7 days and a lag of 3 days. The identified appropriate support scales and lags can be used for low flow forecasting with a lead time of 14 days.

Key words low flows; standardized groundwater storage index; rank correlation; support scale; time lag; Main River, Germany

INTRODUCTION

Hydrological studies and subsequent modelling efforts require basic knowledge of flow processes and their spatial and temporal variations (Beven, 1995; Booij, 2002, 2005). The flow processes occur at a wide range of scales, from flash-floods of several minutes duration to flow in groundwater aquifers over many decades (Blöschl & Sivapalan, 1995). The flood forecasts are made at small temporal scales (e.g. hourly) to explain fast runoff processes. However, since low flow is a slow process, the low flow forecasts are made at longer temporal scales.

Low flow is defined as a seasonal phenomenon that is normally sustained by groundwater discharge or surface discharge from lakes, marshes or melting glaciers, and it is an integral phase of a flow system of any river (Smakhtin, 2001). It can negatively affect the main functions of a river, for example, irrigation, industrial water supply, cooling water for the energy sector, freight shipment and ecological and recreational activities. The indicators of low flow can be different, but dominant indicators, such as groundwater storage, precipitation, lake levels and evapotranspiration, act on more or less regular time scales. These indicators influence low flows at different temporal and spatial scales depending, obviously, on the indicator itself, but also on climatological and geographical characteristics (Beven, 1995). The objective of this study is to investigate appropriate temporal scales of three pre-selected dominant indicators: precipitation, evapotranspiration and groundwater. The Main River basin is used as a case study.

The second section gives an overview of raw data and the Main River basin. The third section addresses the steps we used to investigate the temporal scale relations. The fourth section discusses the results, and finally conclusions are drawn.

STUDY AREA AND DATA

The Main River is 524 km long and its basin area is 27 200 km^2. The average annual precipitation is 765 mm, the average evapotranspiration is 535 mm and the average runoff is 230 mm. This results in a runoff coefficient of around 0.3, which is low compared to other major sub-basins in

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the Rhine basin. The maximum elevation in the basin is about 700 m. There are large forest areas in the west, northeast and southeast parts of the basin. Crops are grown in the entire basin and a small amount of grass-covered areas were observed from the current land-use maps. In addition, the urbanisation density is high in the western and southeastern parts of the basin.

Table 1 indicates the data used such as the daily discharge at Osthafen (Q). The period for all data was 1974–2002. The groundwater dataset contained 107 groundwater measurement stations from two states (i.e. Hessen state with 52 stations and Bayern states with 55 stations). Low flow is defined as the flow value below the Q75 exceedence threshold in the flow duration curve.

Table 1 Summary of the raw data.

Data type	Resolution	Source	Scale
Discharge	Point	GRDC	Daily
Precipitation	Sub-basins (734~2422 km^2)	BfG	Daily
Evapotranspiration	Sub-basins (734~2422 km^2)	BfG	Daily
Groundwater level	Point	Hessen and Bayern states	Weekly and monthly

METHODOLOGY

As a scale investigation, correlation analysis was employed to low flows and dominant indicators with varying support scale and varying lag to identify at which scale and lag the interaction between low flows and indicator was highest. The followed two steps are:

(a) Basin averaging of the pre-selected dominant low flow indicators,
(b) Correlation assessment (Pearson, Spearman and Kendall tests).

Since our particular interest was to use the identified appropriate scales in a low flow forecasting with a lead time of 14 days, we applied this lead time as an additional lag in the correlation assessment.

Estimating daily standard storage index

Groundwater levels from 16 sub-basins of Main River were used to estimate basin storage index. The data series were extracted from two German states at two different temporal resolutions. Hessen state data was at a weekly scale and Bayern state data was at a monthly scale.

Firstly, the Hessen data were aggregated from a weekly to a monthly scale. Secondly, the stations in each sub-basin were standardised, and then they were merged using the arithmetic mean. To downscale monthly storage index to daily storage index, we used linear interpolation. The basin averaging of daily storage index from 16 sub-basins is elaborated in the following section.

Basin averaging of the pre-selected dominant low flow indicators

The daily P and daily ET data were provided as sub-basin averaged values for 16 sub-basins of the Main River as implemented in the HBV model for the Rhine basin (Renner *et al.*, 2009). The sub-basin averaged P, ET, and G data were aggregated using standardized values of the 16 sub-basins. The data were then averaged using area weights. Finally, three dominant low flow indicators, P, ET, and G (standard storage index) are represented by three basin averaged time series. Figure 2 shows seasonal oscillation of groundwater storage and ET in the entire basin.

Correlation assessment

In this part, different correlation coefficients are considered, namely the Pearson correlation coefficient and two rank correlation coefficients that are Spearman's ρ and Kendal's τ (Tallaksen & van Lanen, 2004). Rank correlations are more robust techniques and less sensitive to noise and extreme values. They are also effective for nonlinear and non-monotonic relationships instead of the

Pearson correlation coefficient, which can only be applied to linear relationships (Wedgbrow *et al.*, 2002). The correlation coefficients were estimated between low flows and dominant low flow indicators (i.e. P, ET and G) with a lead time of 14 days and varying support scales of dominant low flow indicators and varying lag times between low flows and indicators (Fig. 1). The support scales varied from 1 day to 336 days and lags varied from zero days to 210 days. The daily low flow series of the Main basin is re-constructed based on the Q75 threshold value, i.e. 94.5 m^3/s. The low flows are aggregated to 3-day low flows as average of one day before, and one day after the prediction

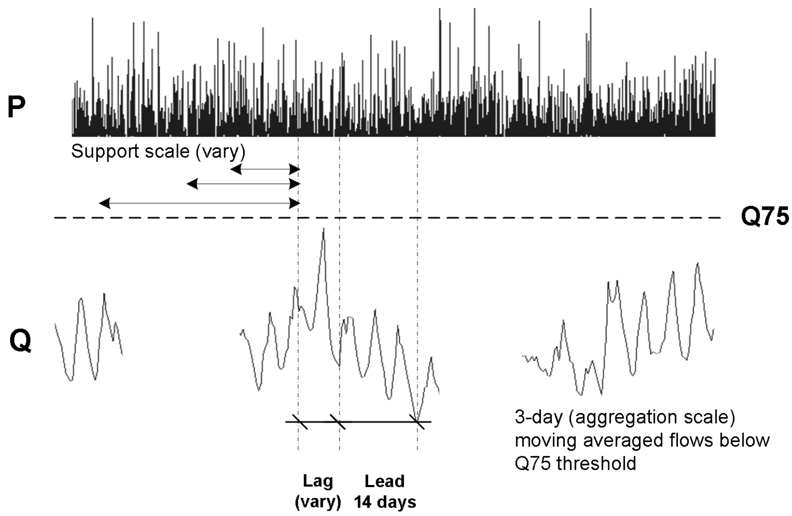

Fig. 1 Conceptual diagram illustrating the correlation assessment of 3-day moving averaged low-flow data and precipitation data with varying temporal support scale and varying lag (days).

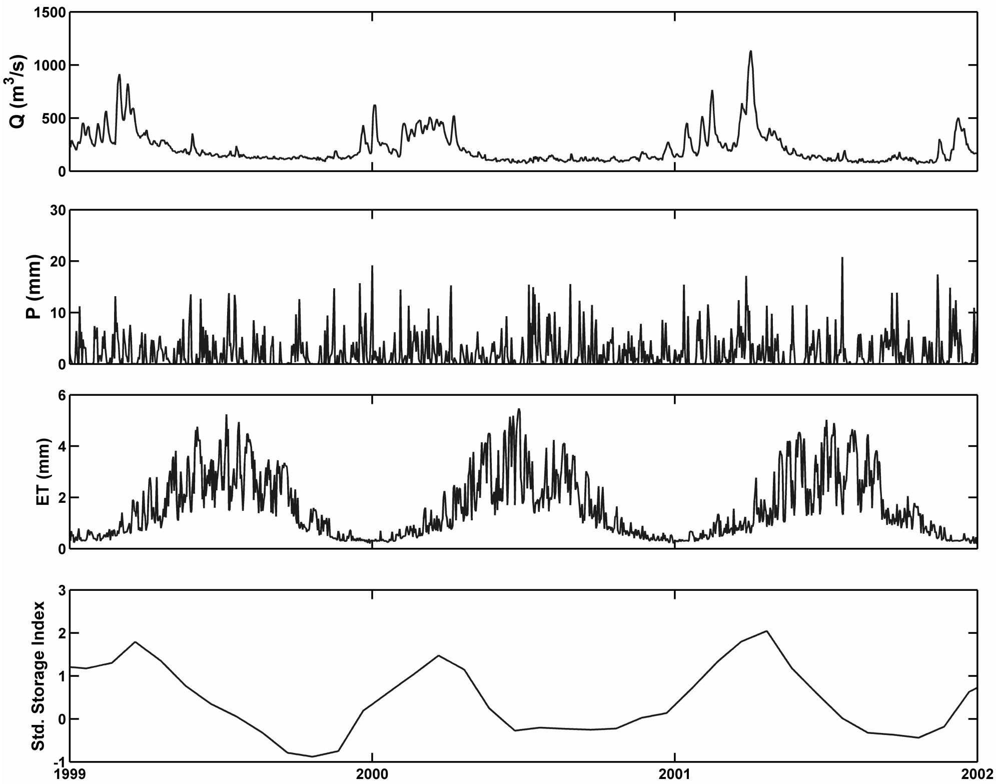

Fig. 2 Observed daily time series of Q and pre-selected low flow indicators P, ET and G.

time. The aggregation level of 3 days and the lead time of 14 days were subjectively selected according to our main interest of low flow prediction with a lead time of 14 days. Moreover, the forecast of 3-day averaged flow is assumed to be reasonable compared to the lead time of 14 days. The operational value of both 3-day low flow forecasts and daily forecasts are almost the same for the navigation and energy sectors, which are the most important economical river functions.

RESULTS AND DISCUSSION

Basin averaging the pre-selected dominant low flow indicators and estimating daily standard storage index

Figure 2 shows discharge series and corresponding basin averaged P, ET and standard storage index. The last 3 years of the dataset are focused to indicate the seasonal variations.

The G data was examined by a correlogram to select a suitable downscaling method from monthly to daily storage index. The correlogram for two stations with a relatively high variability (standard deviation) of the groundwater level revealed long correlation lengths that are 9 and 11 weeks. A scale of 2 weeks was revealed as we applied the rule of thumb, taking 25% of the correlation length as an appropriate temporal scale (see e.g. Booij, 2003). This investigation showed that using the downscaling method from a monthly to a daily scale is a simple way to record data. Hence, the linear interpolation method was applied for data in-filling by assuming that the measurements were made in the middle of each month. The daily standard storage index for the Main River was then used in the correlation assessment, in addition to P and ET data.

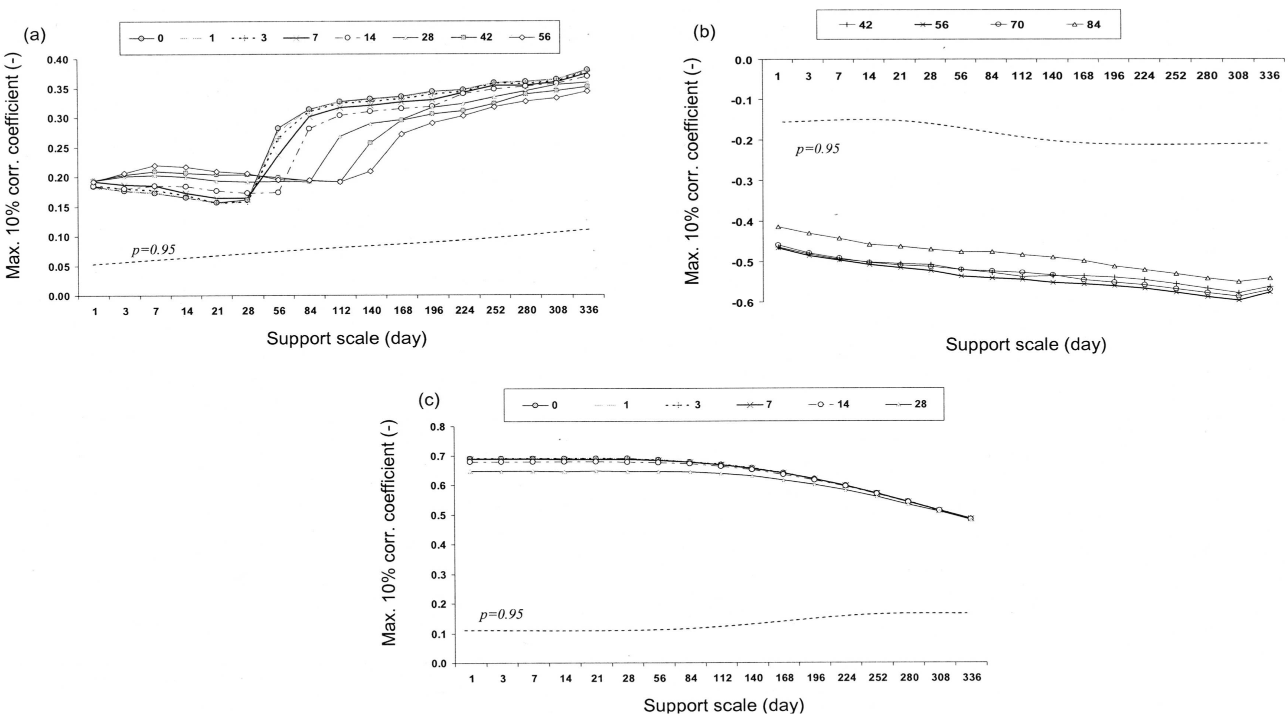

Fig. 3 Spearman correlation coefficient (rho) between 3-day low flows at Osthafen and different variables with a lead time of 14 days; and varying lag time (days) as a function of varying temporal support scale (days) of low flow indicators (a) Q-P (b) Q-ET and (c) Q-G.

Correlation assessment

Figure 3 shows the Spearman cross correlation coefficients between low flows and dominant indicators as a function of the support scale and lag. Different support scales and lags were found to be appropriate for P, ET, and G. Table 2 shows the results using three different correlation techniques. The results of the two rank correlation analysis techniques were very similar to the Pearson correlation coefficients indicating that inter-relations between low-flows and indicators are more or less linear in large scales. Moreover, the perturbation of the outlier data must be limited as Pearson coefficient is normally sensitive to extreme values. With these validated correlation coefficients, the identification of appropriate lag and support scales for the low flow indicators could be done. There is an increasing trend in P-Q correlation coefficients (Fig. 3(a)) with increased support scale. The negative ET-Q correlation coefficient (Fig. 3(b)) increases up to 280 days of the support scale. The G-Q correlation coefficient decreases after 56 day support scale (Fig. 3(c)). Since the groundwater storage changes slowly, the appropriate support scale of G is small (7 days). Moreover, it is steadier than support scale of *P* and *ET*.

Table 2 The range of support scales and time lags resulting in a correlation coefficient within the maximum 10% percentile estimated by three different methods.

Methods	P		ET		G	
	Scale	Lag	Scale	Lag	Scale	Lag
Spearman	196–336	0–56	84–280	42–84	1–280	70–126
Pearson	280–336	0–28	56–280	42–98	14–224	84–112
Kendall	252–336	0–28	56–280	42–98	1–252	84–112

The overlapping figures of different support scales for ET and G explicitly shows the seasonal character of these slow processes. The lag period for G is remarkably long compared to the lag period for P and ET. Three- to 4-month lag indicates that the change in the half-year groundwater storage in the previous season has an affect on low flow occurrence. It can be concluded that the low flows in the Main basin are closely related to the pre-selected indicators, in particular, G with long memory.

CONCLUSION

Three correlation analysis techniques were applied for different combinations of dominant low flow indicators and low flow series based on a fixed lead time of 14 days, and varying lag and varying support scale. The aim was to reveal appropriate temporal scales of pre-selected low flow indicators for low flows. The results show that the three techniques gave similar correlation coefficient figures. Moreover, the dominant low flow indicators P, ET and G have significant correlations; in particular, G and ET have higher correlations than P. The pre-selected dominant low flow indicators P, ET and G with identified lag and support scale will be used in a seasonal low flow forecast with a lead time of two weeks.

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