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Identification of appropriate lags and temporal resolutions for low flow indicators in the River Rhine to forecast low flows with different lead times

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Abstract:

The aim of this paper is to assess the relative importance of low flow indicators for the River Rhine and to identify their appropriate temporal lag and resolution. This is done in the context of low flow forecasting with lead times of 14 and 90 days. First, the Rhine basin is subdivided into seven sub-basins. By considering the dominant processes in the sub-basins, five low flow indicators were selected: precipitation, potential evapotranspiration, groundwater storage, snow storage and lake storage. Correlation analysis was then carried out to determine the relationship between observed low flows and preselected indicators with varying lags (days) and temporal resolutions (from 1 day to 7 months).

The results show that the most important low flow indicators in the Alpine sub-basins for forecasts with a lead time of 14 days are potential evapotranspiration with a large lag and temporal resolution, and lake levels with a small lag and temporal resolution. In the other sub-basins groundwater levels with a small lag and temporal resolution are important in addition to potential evapotranspiration with a large lag and temporal resolution. The picture is slightly different for forecasts with a lead time of 90 days. The snow storage in the Alpine sub-basins and the precipitation in the other sub-basins also become relevant for low flows. Consequently, the most important low flow indicators in the Alpine sub-basins for forecasts with a lead time of 90 days are potential evapotranspiration with a large lag and temporal resolution, lake levels with a small lag and temporal resolution and snow storage with a small lag and large temporal resolution. The resultant correlation maps provide appropriate lags and temporal resolutions for indicators to forecast low flows in the River Rhine with different lead times. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS River Rhine; low flows; temporal resolution; lag; appropriate modelling; correlation analysis

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INTRODUCTION

Forecasting low flows several weeks or months in advance can benefit the management of water resources, river navigation and cooling water supply for the energy sector, particularly in Europe, where heavily industrialised cities are usually located along rivers. A two-week forecast is often useful for the freight shipment sector whereas a longer lead time forecast like three-month low flow forecast is a crucial reference for contingency plans of the energy sector. The water authorities can then make operational decisions on river traffic (e.g. maximum load allowance for ships), or decisions on reducing energy production because of a low cooling water supply.

Many different hydrological models exist which describe the transformation of rainfall to runoff at different spatial and temporal scales (Anderson *et al.*, 2004; Hattermann *et al.*, 2004; Hannaford *et al.*, 2011). Statistical models have been used to estimate low flows (Ouarda *et al.*, 2008), and conceptual models were applied to long-term low flow forecasting in France (Perrin *et al.*, 2002). To the best of our knowledge, none of the previous studies used conceptual and data-driven models to forecast low flows in the River Rhine. Selection of appropriate spatial and temporal scales is important as it affects the required input data, the processes that can be well presented, the scenarios that can be analysed and usefulness of the resulting forecasts (Dumont *et al.*, 2008). However, the selection of a particular spatio-temporal scale in the model is usually not well reported, making the appropriateness of a chosen scale difficult to judge. Furthermore, modellers often have no clear criteria for selecting these scales for forecasting low flows.

This study focuses on identifying appropriate temporal scales (defined here as resolution) of dominant low flow processes (defined here as indicators). Identification of appropriate spatial scales is beyond the scope of this study. We present a framework for selecting the appropriate lag between the indicator and observed low flows and appropriate temporal resolutions of the indicators to include in the model or for selecting a suitable model for low flows. The lag provides information on the response time of the basin, including concentration time and travel time, while the temporal resolution gives information on the scale of the water volume entering or leaving the system.

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Different processes can be dominant for different lead times (Klemeš, 1983; Haltas and Kavvas, 2011). There have been studies in which the hydrological processes leading to low flows and the relationship between low flows and drainage area were assessed (Burn *et al.*, 2008; Khaliq *et al.*, 2008; Ouarda *et al.*, 2008; Spence *et al.*, 2008). Most of these studies focused on low flows in Canadian rivers.

The river discharge during a low flow period mainly originates from groundwater storage, and the outflow follows a characteristic recession curve (Schneider, 2008). Basin characteristics such as geology, soil type, topography, vegetation, hydraulic conductivity and extent of the aquifer determine the magnitude and timing of groundwater discharge to streams (Hattermann *et al.*, 2004; Burn *et al.*, 2008; Allen *et al.*, 2010). Apart from that, the release from other large storages controlled by gravity, such as large lakes, snow storage and glaciers, can be important in sustaining low flows (Tallaksen and Van Lanen, 2004; Suweis *et al.*, 2010).

Low flows may occur in any season, mainly due to the lack of water input into a basin over a long period. This can be a dry period with a climatic water deficit (summer low flows) or a period with temperatures below zero, when the storage of precipitation is in the form of snow (winter low flows). Low flow is, therefore, defined as a seasonal phenomenon and an integral phase of the discharge cycle (Smakhtin, 2001; Warmink *et al.*, 2010).

Several studies have been carried out to analyse characteristics of low flows. Booij and de Wit (2010) analysed the relationship between the annual discharge deficit resulting in low flows and the annual minimum spatially averaged precipitation at different temporal scales for the River Meuse in France and Belgium. Their study showed that the relationship becomes more significant at larger temporal scales. However, the central date of occurrence of spatially averaged annual minimum precipitation did not show any relationship in time, while the annual discharge deficit mostly is observed in the period August–October. This is obviously because the annual cycle of evapotranspiration dominates the discharge deficit and the occurrence of low flows. Gudmundsson *et al.* (2011) analysed a pan-European dataset of 615 streamflow records, summarised as time series of annual streamflow percentiles. They revealed that under dry conditions, the catchment response is more complex, as it depends on storage characteristics. Tallaksen *et al.*(2009) showed the importance of processes in modifying the drought signal in both time and space for the Pang catchment, UK. Their study disclosed that meteorological droughts frequently cover the whole catchment and last for a relatively short period (1–2 months). Moreover, hydrological droughts (e.g. groundwater drought) cover smaller areas and last longer (4–5 months) than meteorological droughts. Yue and Wang (2004) showed that low flows in Canadian rivers generally exhibit simple scaling behaviour, and the drainage area alone explains most of the variability in the statistical properties of low flows.

In this study, the main meteorological drivers in the River Rhine (precipitation and potential evapotranspiration) and the aforementioned storages (groundwater, lakes and snow) are defined as low flow indicators. It should be noted that, these relevant low flow indicators were not arbitrarily selected, but are based on previous reports (e.g. Belz and Frauenfelber-Kääb, 2007; Hurkmans *et al.*, 2008; Hurkmans *et al.*, 2010). We use the term ‘indicator’ rather than ‘process’ throughout the study, since not all the preselected indicators correspond to a hydrological process (e.g. lakes). The indicators usually act at different scales in the basin. While large storages are dominant at very large spatio-temporal scales, other indicators can be well described in small scales. However, these indicators can be modelled in an appropriate model scale.

Here, ‘appropriateness’ is defined as a level between complex and simple for a model and its inputs. An appropriate model should then give adequate results through the use of appropriate input scales and a corresponding appropriate model scale. This is because the dominant processes are considered at their appropriate spatial and temporal scales. Consequently the appropriate model scale is estimated by integrating all input scales (Booij, 2003).

A model appropriateness procedure has been developed by Booij (2003). It has been cited in other studies as ‘getting the right answers for the right reasons’ (Kirchner, 2006). The procedure includes identification of dominant processes, appropriate scales and associated appropriate process formulations. In his study, Booij (2003) explored appropriate spatial scales for precipitation, elevation, soil and land use in a large river basin by using different relationships between scales and variable statistics and outputs for river basin modelling purposes. A framework was used to integrate the identified scales into an appropriatele model scale of about 10 km with a corresponding temporal scale of 1 day. This result can drastically reduce the size of input data and model complexity. Booij (2002a) examined the effects of different spatial and temporal precipitation and hydrological model scales on extreme river flows. A spatial scale of 40 km was estimated to be appropriate for precipitation input into the model (Booij, 2002a). This agrees with the appropriate precipitation scale of about 20 km as assessed by Booij (2002b) for the same river basin.

To the best of our knowledge, none of the previous studies focused on quantifying the appropriate lag and temporal resolution of low flow indicators to forecast low flows. This is particularly important for modellers to develop a basin specific data-driven model or to select a model from existing hydrological models that is appropriate for low flow forecasting and for river managers. The importance of this research topic of identification of space-time patterns to improve large-scale hydrological predictions by considering uncertainties was also emphasised in a recent special issue of a hydrological journal (Cloke and Hannah, 2011; Gudmundsson *et al.*, 2011; Hannaford *et al.*, 2011).

Understanding dominant low flow indicators and their relationship to low flows in the River Rhine will help to improve the analysis of river behaviour during low flows and better identify the components of a low flow forecast model. This study is a first attempt that includes the most important low flow indicators and analyses their linkage to observed low flows for different temporal lags and resolutions.

In the following, the study area and data are described (Section 2). This is followed by the general structure of our lag and temporal resolution framework and details of the different basin averaged indices which form the basis of the correlation analysis (Section 3). Subsequently, the results are discussed (Section 4), and finally conclusions are drawn (Section 5).

STUDY AREA AND DATA

Study area

The Rhine is the busiest inland waterway in Western Europe. It connects cities with heavy industry to the world market via Rotterdam harbour in the Netherlands. The river originates at the outlet of Lake Toma in the Piz Badus (2928 m), Swiss Alps (Figure 1). It flows along a 1233 km long course before discharging into the North Sea.

The surface area of the Rhine basin is approximately 185 300 km^2, covering major parts of Switzerland, Germany, Luxembourg, France and the Netherlands, and has nearly 60 million inhabitants (Huisman *et al.*, 2000). Furthermore, more than 60% of the Dutch fresh surface water comes from the Rhine (Middelkoop and Van Haselen, 1999). The topography of the basin varies from 4000 m in the Alps to 6 m below sea level in the Netherlands.

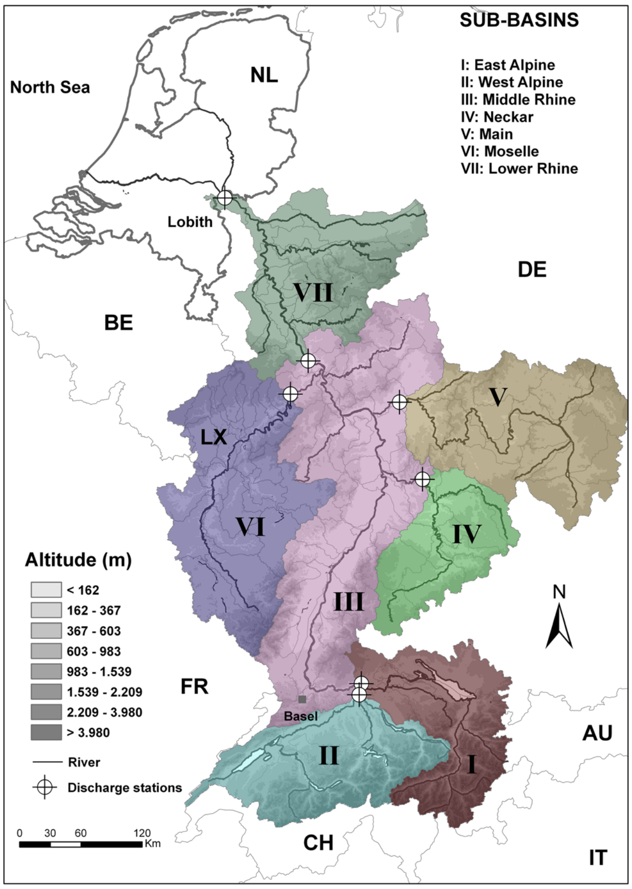

Figure 1. Schematisation of the seven major sub-basins of the River Rhine upstream of Lobith on the German-Dutch border

The average discharge before Lake Constance, located in the East Alpine (EA) sub-basin (Figure 1), is approximately 1000 m^{3}s^{-1}. This is an indication of the Alps' contribution to the total discharge. It then increases to up to 2300 m^{3}s^{-1} on average at the German-Dutch border (Lobith). The discharge regime of the Rhine at Basel is mainly dominated by meltwater from snow and around 150 Alpine glaciers, including those in the Gotthard massif (Figure 1). Here, the water is generally at its highest level in spring and early summer, when the snow melts (Figure 2). More than 70% of the summer flow at Lobith (Figure 1) originates from the Alps, whereas only about 30% of the winter flow comes from the Alps (Middelkoop and Van Haselen, 1999), because winter precipitation is stored as snow in this part of the basin until it melts in late spring (Figure 2).

The tributaries Neckar, Main and Mosel join the Rhine in Germany. These tributaries carry vast volumes of water, mainly in winter, when there is intense rainfall and negligible evapotranspiration. Figure 2 shows that the snowmelt water and rain ensure that the River Rhine is navigable all year long. In addition, the difference between the minimum and the maximum flow in the Rhine is only a factor of 20, while it is a factor of around 150 in the neighbouring rainfed Meuse (Middelkoop and Van Haselen, 1999).

The hydrology of the Rhine basin has been modelled with a conceptual model (HBV) using 134 catchments (Te Linde *et al.*, 2008; Te Linde *et al.*, 2010). As we are interested in major storages in the basin and their relationship to low flows, the Rhine basin is analysed on two spatial scales that of 134 catchments and that seven sub-basins. The latter level of discretisation is chosen on the basis of basin characteristics such as topography and geology. The upper Rhine is divided into West Alpine (WA) and EA, to distinguish Lake Constance's impact on low flows in addition to that of snow storage in the Alps. The EA and WA sub-basins cover approximately 34 000 km^2, with a maximum altitude of 4000 m. There is great variability in altitude and subsequently in slopes, showing the heterogeneous topography in the WA and EA sub-basins (Table I). The glaciers cover about 400 km^2 of this mountainous area. The EA sub-basin stretches from the beginning of the river to Lake Constance (Alpenrhein), while the WA sub-basin covers the River Aare basin with an outlet in the Untersiggenthal before Basel (Hochrhein). The Untersiggenthal discharge station on the Aare covering 71% of the total surface area of the WA sub-basin is chosen to represent WA sub-basin discharge. This leads to a clear picture of two Alpine sub-basins with totally independent discharge regimes. Moreover, estimating the annually generated discharges become easier as it is the fraction of the independent discharge regimes to the sub-basins' surface areas (see Table I). Note that the

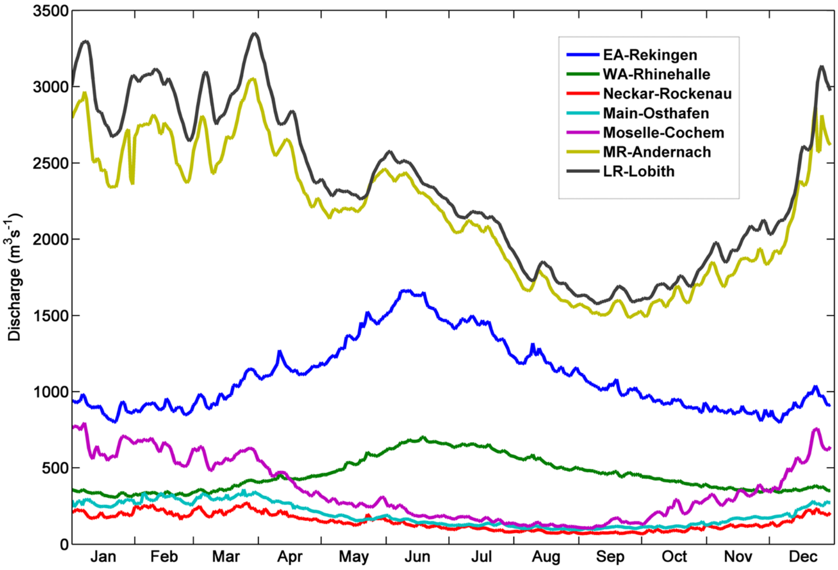

Figure 2. Long-term average discharge recorded at the outlets of the seven major sub-basins

Table I. Spatial characteristics of the seven major sub-basins shown in Figure 1

Sub-basin	Area [km^2]	Annually generated discharge [mm]	Altitude [m] Range	Mean	Std. dev.
East Alpine (I)	16 051	890	143–3270	1250	761
West Alpine (II)	17 679	1021	252–3980	967	603
Middle Rhine (III)	41 473	344	67–1340	309	205
Neckar (IV)	12 616	363	90–970	432	156
Main (V)	24 833	244	83–939	344	115
Moselle (VI)	27 262	410	59–1326	340	131
Lower Rhine (VII)	20 174	273	5–779	237	150

independent discharge is estimated by subtracting all inlet discharges from the outlet discharge.

In previous Rhine studies, Rheinfelden discharge station near Basel was used for hydrological modelling purpose (Renner *et al.*, 2009).

The Middle Rhine (MR) is divided into four parts: the Neckar, Main and Moselle tributaries and the remaining main channel between Basel and Koblenz, which is called the MR. The seventh sub-basin, the Lower Rhine (LR), starts after Koblenz, where the Main and the Moselle flow into the Rhine. Previous studies focusing on the Rhine basin used a similar subdivision into seven sub-basins (e.g. Belz and Frauenfelber-Kääb, 2007).

Discharge data and preselected low flow indicators

We use different hydrological variables to carry out the correlation analyses (see Table II). Daily precipitation and potential evapotranspiration data as spatially averaged for 134 catchments were obtained from the German Federal Institute of Hydrology (BfG) in Koblenz (Germany). The outlet discharges for the EA (*station #6935054 at Rekingen*), WA (*station #6935300 at Untersiggenthal*), Neckar (*station #6335600 at Rockenau*), Main (*station #6335304 at Frankfurt Osthafen*) and Mosel (*station #6336050 at Cochem*) and independent discharges for the MR and LR were used in the correlation assessment.

Table II. Data characterisation/ availability

Data	Index	Spatial resolution	Number of stations/sub-basins	Period	Temporal resolution	Source
Discharge	Q	Point	7	1974–2008	Daily	GRDC in Koblenz
Precipitation	P	Sub-basins	134	1951–2006	Daily	BfG in Koblenz
Evapotranspiration	PET	Sub-basins	134	1950–2006	Daily	BfG in Koblenz
Groundwater levels	G	Point	1402	1986–2009	Weekly, monthly	German states and BAFU.ch
Snow	S	Point	40	1978–2008	Daily, monthly	SLF.ch
Lake levels	L	Point	11	1978–2008	Daily	BAFU.ch

Daily lake level (L) and daily fresh snow depth data (S) are also included in the correlation analysis. The groundwater data (G) comprise time series of levels measured at 1404 stations throughout the Rhine basin with different data lengths and temporal resolutions (Table II). Also, the stations were not distributed evenly throughout the basin (Figure 3). For example, the groundwater levels in Bavaria in Germany are represented by a network of 661 wells, while only 99 wells were available in Switzerland. Therefore, pre-processing of groundwater level data was required.

The data used are summarised in Table II.

METHODOLOGY

Overview

This study employs a five-step framework to assess the relative importance of low flow indicators for the River Rhine and to identify their appropriate temporal lag and resolution (Figure 4). The low flow indicators were selected and analysed on the scale of seven sub-basins.

We define seven sub-basins by spatially aggregating the 134 catchments according to similar hydrological characteristics and based on previous studies (e.g. Belz and Frauenfelber-Kääb, 2007; Hurkmans et al., 2008). These sub-basins are the large tributaries except for the Middle and LR sub-basins that are the remaining parts. Note that 134 catchments in the Rhine basin, shown in Figure 4, had already been identified and used in other Rhine studies for modelling purposes (e.g. Te Linde *et al*., 2008; Reggiani *et al*., 2009; Renner *et al*., 2009). The scale of seven sub-basins is assumed to be sufficient to understand the preselected indicators and their relationship to low flows at the basin outlets. This raises the question of why the assessment of low flow indicators was not applied on the scale of 134 catchments. Identification of low flow indicators can be very complicated due to interacting processes on small scales, since the low flows are, in general, sustained by baseflow originating from a groundwater reservoir, which generally has a much greater spatial scale than the typical scale of each of the 134 catchments. Therefore, the relationship between low flows and indicators on the scale of 134 catchments can lead to misinterpretation of existing storages in the Rhine basin.

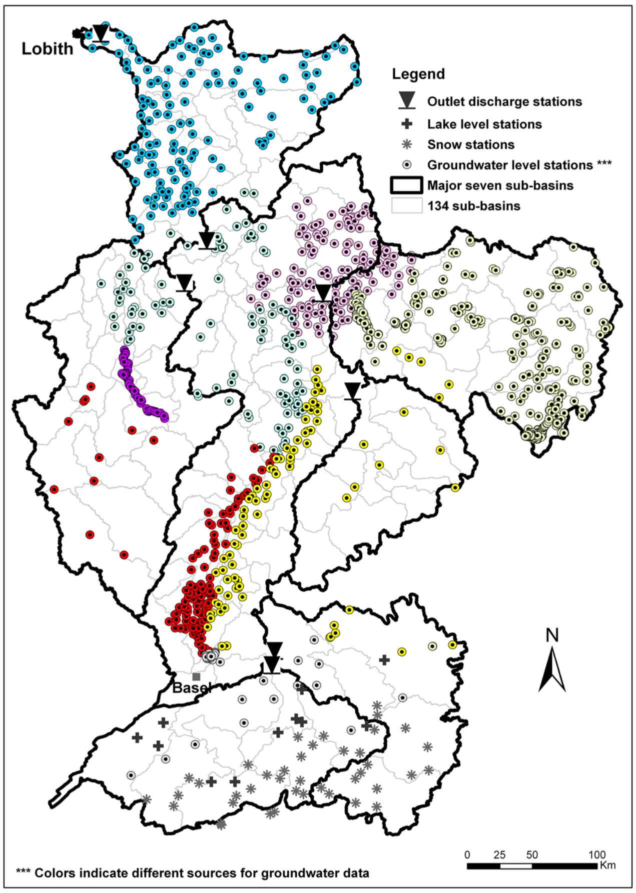

Figure 3. Location of discharge, lake level, snow depth and groundwater level stations

In step 2, we selected precipitation (*P*), potential evapotranspiration (*PET*) and groundwater storage (*G*) as low flow indicators in all seven sub-basins. Additionally, snow storages (*S*) and lake storages (*L*) are considered as indicators, but only in the two upstream sub-basins (EA and WA) (Verbunt *et al*., 2003; Scherrer and Appenzeller, 2006; Zappa and Kan, 2007; Tague and Grant, 2009).

In step 3, data at the point or catchment (134 catchments) scale were aggregated to the scale of seven sub-basins. This is done so as to have one basin-averaged time series for each indicator.

We used a classical standardisation method to avoid effects of spatial heterogeneity in the data. The standardised data have a zero mean and a standard deviation of one. The standardised series are obtained by subtracting the mean from each element and dividing it by the standard deviation of the original series (Equation (1)).

$$Z = \frac{X - \mu_x}{\sigma_X} \tag{1}$$

where Z is the standardised time series, X the original time series (observed data), μ_x the mean of the original time series and σ_X the standard deviation of the original time series.

In step 4, the temporal resolution of the indicators is varied between 1 day and 336 days (i.e. 1, 3, 7, 14, 21, 28, 56, 84, 112, 140, 168, 196, 224, 252, 280, 308 and 336 days). The lag between indicator and low flows is varied between 0 and 210 days (i.e. 0, 1, 3, 7, 14, 28, 42, 56, 70, 84, 98, 112, 126, 140, 154, 168, 182, 196 and 210 days). The maximum temporal resolution of 336 days and maximum lag of 210 days are assumed to be sufficient, as these ranges allow us to scan a long period of more than 18 months. To the best of our knowledge, only large-scale atmospheric indicators can be significant over longer periods than those examined here.

Following the relevant reports by the principal authority for low water levels in the Netherlands, i.e. Dutch National Coordinating Committee on Water Distribution (LCW), we selected the exceedence probability

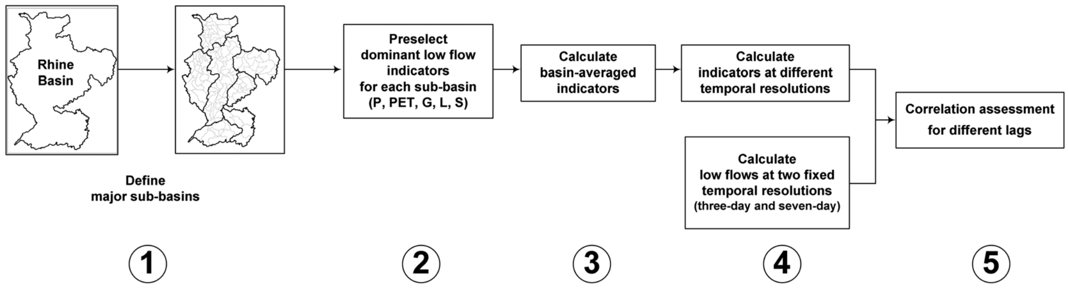

Figure 4. General framework for assessing the relative importance of low flow indicators for the Rhine and identifying their appropriate temporal lag and resolution

75% (Q75) as a threshold for the definition of low flows. Low flows at this threshold are still affecting the previously described river functions, and the number of days with low flows is sufficient to calibrate a forecast model.

Daily discharges observed at Lobith station equal to or below this threshold are used to construct the reference low flow series. The low flow occurrence days at Lobith are then used to construct low flow series for all seven major sub-basins, since our objective is to forecast low flows at Lobith.

These seven Lobith-based low flow series are temporally aggregated on the scale of 3 and 7 days for two lead times, namely 14 and 90 days, respectively. The operational value of daily-averaged and 3-day averaged low flow forecasts is about the same for the navigation and energy sectors. Moreover, forecasting 3-day averaged flow is assumed to be reasonable with a lead time of 14 days (De Bruijn and Passchier, 2006). Similarly, the temporal resolution is increased to 7 days when the lead time is 90 days. Correlation coefficients between low flows and indicators are estimated in step 5, to assess the relative importance of low flow indicators and to explore for which lag and temporal resolution the correlation is most significant.

Definition of storage indices

Daily standard groundwater storage index. Groundwater levels from numerous stations in the Rhine basin were included in this study. The individual groundwater stations' measurements, shown in Figure 3, were aggregated to the scale of seven sub-basins using standardised data (Equation (1)). Therefore, they are hereafter called standard groundwater storage indices.

It should be noted that the temporal resolution of the groundwater data is either weekly or monthly. For example, the groundwater data series from Bavaria are available with a monthly resolution, while the remaining part of the dataset has a weekly resolution. The differences in resolution are eliminated, first, by aggregating weekly into monthly data. This is done for every sub-basin where both weekly and monthly data are found. Particularly, in the west of the Main sub-basin, there are catchments with weekly data from Hessen and monthly data from Bavaria (see Figure 3). After the aggregation of weekly data into monthly data, the stations in each of the 134 catchments are standardised and then merged using arithmetic means, to estimate standard monthly storage index series. Disassembling these monthly storage index series to the daily scale is accomplished through linear interpolation. Since groundwater storage oscillations are generally very slow, a linear character is assumed for the data. This assumption was tested using a temporal correlogram. We examined the temporal variability of groundwater data in one of the seven major sub-basins. We selected nine stations in the western part of the Main sub-basin, where both weekly and monthly data are found. The temporal correlogram of stations with highly variable groundwater levels showed that they have long correlation lengths, varying from 9 to 11 weeks. The appropriate temporal scale can be defined as 25% of the correlation length, accepting a bias of 10% (Booij, 2003). Therefore, a scale of 2 weeks was estimated as an appropriate temporal scale. For that reason, the linear interpolation method was applied, assuming that the measurements were taken in the middle of each month.

The standard lake level index and the standard snow storage index were estimated only for the EA and WA sub-basins.

Daily standard snow storage index. Daily fresh snow depth data in the EA and WA sub-basins were used to estimate the standard snow storage index. Some of the small Alpine basins have more than one snow-monitoring station. Therefore, first, the data from the stations within the same sub-basin were standardised using zero mean and a standard deviation of one, and, second, these stations were merged to the scale of 134 catchments using the arithmetic mean.22

Daily standard lake storage index. There are several large lakes in the EA and WA sub-basins. We selected Lake Constance as representative of the lake storage in the EA sub-basin. Daily lake levels from ten lakes in the WA sub-basin were used to calculate the daily lake storage index for the WA sub-basin. The data from these lakes were standardised using zero mean and a standard deviation of one. The stations were then merged using the arithmetic mean. For the EA sub-basin, the correlations between the observed lake levels of Lake Constance and low flows for different lags and temporal resolutions were estimated directly.

Basin averaging of preselected low flow indicators from the scale of 134 catchments to that of seven sub-basins

The sub-basin averaged standard daily indices, i.e. *P, PET, G* and *S*, were aggregated to the scale of seven sub-basins using areal weighting. This refers to the fraction of a sub-basin area on the scale of 134 catchments relative to the sub-basin area on the scale of seven sub-basins. The basin-averaged standard groundwater storage index was estimated by using Equation (2).

$$G_{index,j} = \sum g_i \frac{A_i}{A_j} \quad (2)$$

where $i = 1, 2\ldots, 134$ catchments, $j = 1, 2\ldots,$ seven major sub-basins, g_i is the standardised daily groundwater level, A_i the area of each of the 134 catchments and A_j the total area of each of the seven major sub-basins.

The basin-averaged standard snow storage index was estimated by using Equation (3).

$$S_{index,j} = \sum s_i \frac{A_i}{A_j} \quad (3)$$

where $j = 1, 2$ Alpine sub-basins, s_i is the standardised daily fresh snow height series observed in these sub-basins and A_j is the total area of the EA or WA sub-basin.

The basin-averaged standard lake storage index in the WA sub-basin was estimated by using Equation (3).

$$L_{index,j} = \sum l_i \frac{A_i}{A_j} \quad (4)$$

where $j = 2$ indicating WA sub-basin, l_i is the standardised daily lake level series observed in the WA sub-basin and A_j is the total area of the WA sub-basin.

For some of the 134 catchments, no *G*, *S* or *L* data were available, and these catchments were not included in the basin averaging. Finally, each preselected low flow indicator is represented by one series for each of the seven sub-basins. Most of these series are daily standard index series such as *P, PET, G* and *S* for the EA sub-basin, *P, PET, G, S* and *L* for the WA sub-basin and *P, PET* and *G* for the remaining five sub-basins.

Correlation assessment

In the last step of the framework, we used correlation analysis to screen potentially useful predictor–predictant relations for varying lags and temporal resolutions. The correlations were calculated for a lead time of 14 days and 3-day temporally averaged low flows and for a lead time of 90 days and 7-day temporally averaged low flows. The temporal resolution of the predictants (low flow indicators) varied between 1 day and 336 days, whereas the temporal resolution of the predictor (observed low flows) was either 3-day or 7-day moving average values (Figure 5). Note that the forecast lead times (i.e. 14 and 90 days) are added to the lag values in the correlation analysis.

Three different correlation coefficients between low flows and indicators are estimated. We are aware that the Pearson correlation coefficients are based on the assumption of stationary linear relationships between the low flow indicators and low flows (Vicente-Serrano and López-Moreno, 2005; Steinschneider and Brown, 2011). In practice, only slowly responding processes such as groundwater levels and lake and snow storages show linear behaviour (Wedgbrow *et al*., 2002). Since all three correlation coefficients revealed similar results, only the Pearson correlation coefficients are presented.

RESULTS AND DISCUSSION

Basin-averaged daily indicators

Figure 6 shows the basin-averaged low flow indicators in the East Alpine sub-basin for a 3-year period. Because of the fact that the monitoring station at Lake Constance

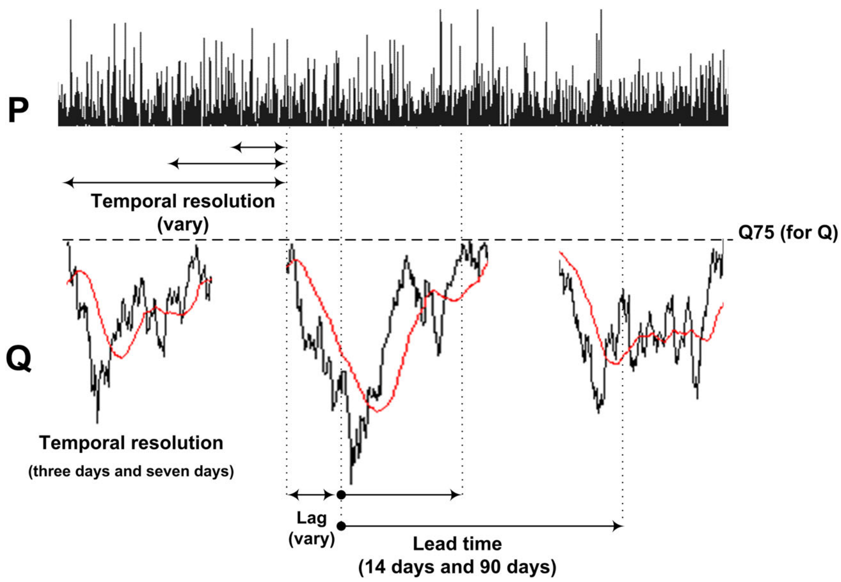

Figure 5. Conceptual diagram illustrating the correlation assessment of 3-day and 7-day moving-averaged low flow data and precipitation data with varying temporal resolutions and lags for lead time of 14 and 90 days

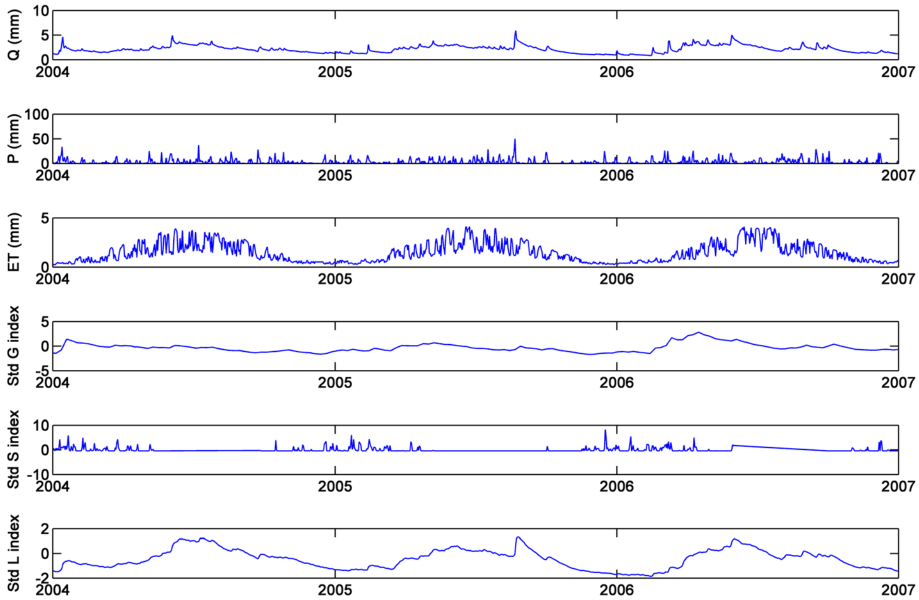

Figure 6. Observed daily time series of Q and preselected low flow indicators P, PET, G, S and L

and the discharge station are close to each other, the fluctuations are very similar.

Correlation assessment

The correlation coefficients between low flows and indicators are presented by using colour maps. In these maps, the *x* axis shows the temporal resolution and the *y* axis the lag between indicators and low flows. The maximum ten percentile of the correlation coefficients in each colour map is indicated by two bars: a vertical bar for the range of lags and a horizontal bar for the range of temporal resolutions. These bars cross at the maximum correlation point, showing the appropriate lag and temporal resolution of an indicator. For clear visibility, the crossing point is also highlighted by a circle. It is assumed that the ranges represent the uncertainty in the appropriate lag and temporal resolution. The correlation coefficients between *PET* and low flows are negative (i.e. blue colour in the maps). However, the absolute value of the maximum correlation for *PET* is used to compare the correlations. The most important features of these colour maps are discussed for each sub-basin, from upstream to downstream. Furthermore, two major questions will be dealt with and discussed. (1) Why has one indicator higher correlations with low flows than other indicators? (2) Why are these lags and temporal resolutions appropriate?

Figure 7 shows the maximum correlation coefficients between indicators and low flows for all sub-basins. The ranking of the low flow indicators will determine the initial forecast model structures. It is obvious that the most important low flow indicators for forecasts with a lead time of 14 days in the Alpine sub-basins are potential evapotranspiration and lake levels, whereas in the other sub-basins in addition to potential evapotranspiration groundwater levels become important indicators (Figure 7a). For forecasts with a lead time of 90 days, potential evapotranspiration, lake levels and snow are the best predictors in the Alpine sub-basins. In the other sub-basins, as well as potential evapotranspiration precipitation or groundwater are important indicators for low flows.

Appropriate lags and temporal resolutions

East Alpine. Figure 8 shows the Pearson correlation coefficients between observed low flows and preselected indicators with varying lags and temporal resolutions in the EA sub-basin. Of the five preselected low flow

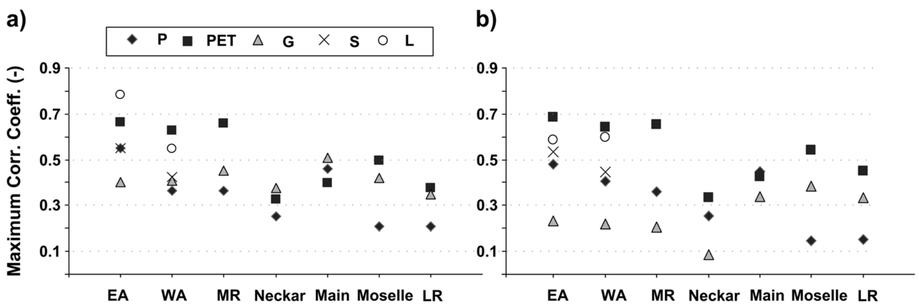

Figure 7. Maximum correlation coefficients between low flows and preselected indicators in the seven sub-basins: a) low flows with a temporal resolution of 3 days and a lead time of 14 days; b) low flows with a temporal resolution of 7 days and a lead time of 90 days. Only for PET were absolute values of correlation coefficients used

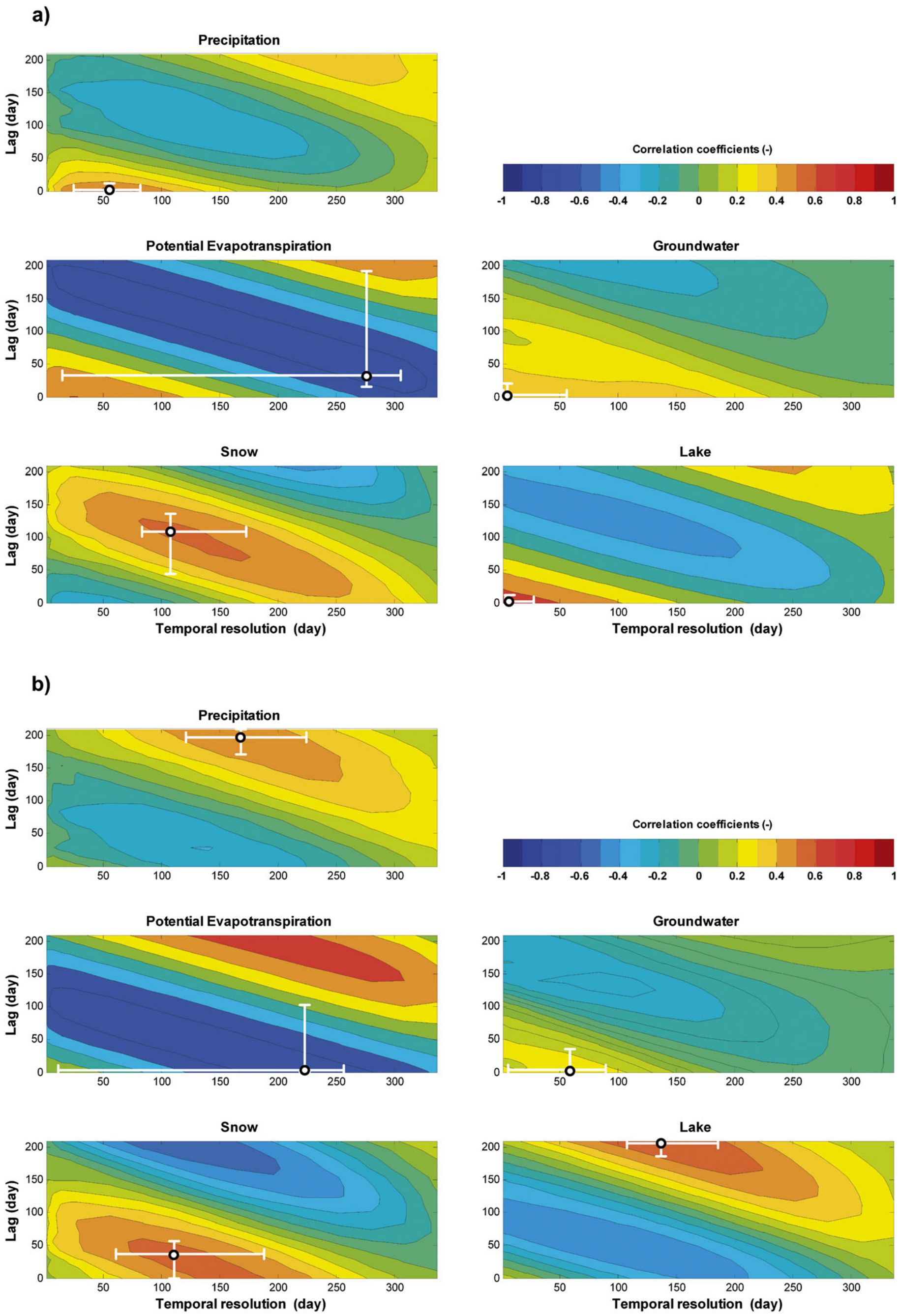

Figure 8. Cross correlation coefficients between low flows in the East Alpine sub-basin and preselected indicators as a function of lag and temporal resolution (days): a) low flows with a temporal resolution of 3 days and a lead time of 14 days; b) low flows with a temporal resolution of 7 days and a lead time of 90 days

indicators, lake levels and potential evapotranspiration revealed the highest correlation coefficients for forecasts with a lead time of 14 days. In addition to these two, snow storage is an important indicator for forecasts with a lead time of 90 days.

The proximity of Lake Constance to the discharge station at Rekingen must be the main reason for high correlations with low flows. The large lake storage in the EA sub-basin (55 km^3) can sustain river flows for several months. Because of the fact that the travel time between the outlet of Lake Constance and the discharge station is very short, small lags (zero days) and daily temporal resolution of lake levels are appropriate for low flow forecasts with lead times of 14 and 90 days. Therefore, the uncertainty around the appropriate lag and temporal resolution for the lake levels is very small.

The correlation maps mainly show two maximum correlation regions, as low flows have high seasonality. This can be clearly seen in the correlation figures for the lake levels. For example, Figure 8a shows the maximum correlation point at a lag of zero days and a temporal resolution of around 1 day for the lake levels, while Figure 8b shows the maximum correlation point at a lag of 210 days and a temporal resolution of around 140 days. Note that the lead times of 14 and 90 days were included in the lags shown in Figure 8a and b, respectively.

Therefore, the maximum correlation point for lake levels in Figure 8b indicates that the lake levels in the preceding 7 months with a temporal resolution of around 5 months are relevant for forecasts with a lead time of 90 days. This corresponds to a total lag of 1 year and can be explained by the annual hydrological cycle. Although this situation is justifiable from a mathematical point of view, such a large lag and temporal resolution are not physically meaningful and should be ignored. Consequently, small lags (zero days) and daily temporal resolution of the lake levels are appropriate for forecasts with lead times of 14 and 90 days, as changes in lake levels are seen directly observed in discharge levels.

Potential evapotranspiration is one of the main driving forces behind low flows, since it determines water loss to the atmosphere. If water storages sustaining river flows such as snow and groundwater are exhausted in a basin, with recurring water deficits, then it is very likely that low flows will be experienced in late summer. This is especially the case for the River Rhine, as most of the summer flow originates from the snow-dominated Alpine sub-basins.

Small lags (42 days) and large temporal resolutions (about 9 months) for the *PET* index are appropriate for forecasts with lead times of 14 days. Moreover, small lags (zero days) and large temporal resolutions (around 7 months) are appropriate for forecasts with a lead time of 90 days. This shows that the *PET* averaged over the preceding summer and winter seasons is an important indicator for low flows at Lobith. However, the uncertainty around the appropriate lag and temporal resolution for *PET* is very large, due to the great climatic variability. The difference between the two lead times can be explained by the additional 76 days in the lag (Figure 8b).

The amount of snow-fall in the preceding winter period must also be a good indicator for the late summer low flows at Lobith. This is what we can see in Figure 8. The maximum correlation for the *S* index for forecasts with lead times of 14 days is found to be at a lag time of about 4 months and a temporal resolution of 4 months, while the maximum correlation for forecasts with lead times of 90 days is at a lag time of about 1 month and a temporal resolution of 4 months. Taking the forecast issue day as August 1, average fresh snow height during the December–March period is important for low flows at Lobith at the end of the summer. The differences found in the appropriate lag and temporal resolutions for the two lead times clearly confirm the effect of the additional lag of 76 days (Figure 8b).

Appropriate lags and temporal resolutions for other indicators are also given in the figures, as they will be tested in the forecasting phase. However, these indicators are less important and are not discussed here for reasons of brevity.

West Alpine. The picture in the WA sub-basin is more or less the same as that in the EA sub-basin. Lake levels and potential evapotranspiration are the most important low flow indicators for forecasts with lead times of 14 and 90 days (Figure 9). However, the maximum correlation between lake levels and low flows in the WA sub-basin for forecasts with a lead time of 90 days is higher than that in EA. We assume that the increase in the maximum correlation for the *L* index in the WA sub-basin is not arbitrary.

The total lake storage in the WA sub-basin, comprised of ten lakes with varying storage capacities, is about 49 km^3. This is relatively less than the storage of Lake Constance (55 km^3). However, smaller lake storage should not be directly interpreted as an indication of shorter memory. First, the annually generated discharge in the WA sub-basin is higher than that in the EA sub-basin. Second, the ten lakes are distributed evenly through the WA sub-basin, whereas there is only one large lake (Lake Constance) in the EA sub-basin. The travel time from lake outlets to the discharge station in the WA sub-basin is longer than that for Lake Constance. Furthermore, the basin-averaged standard lake level index, an aggregated index series for the ten lakes, was used for the WA sub-basin. All this can cause an increase in the maximum correlation between lake levels and low flows for forecasts with a lead time of 90 days (Figure 9b).

The maximum correlations for *L* and *PET* have a similar magnitude and are significantly higher than for the other three indicators. Small lags (zero days) and daily temporal resolution for the *L* index and small lags (56 days) and large temporal resolutions (around 7 months) for the *PET* index are appropriate for forecasts with lead times of 14 and 90 days. The great uncertainty around the appropriate lag and temporal resolution for the *L* index can be explained by the second high correlation region in the upper right part of the correlation map for forecasts with a lead time of 14 days (see Figure 9a). Therefore, the uncertainty range for the maximum correlation point of the *L* index should be from zero to 14 days on the *y* axis (lags) and from zero to 1 month on the *x* axis (temporal resolutions).

Another significant difference between the EA and WA sub-basins is that the snow storage in WA shows weaker correlations than that in EA for forecasts with lead times of 14 and 90 days. This may be because snowmelt water from the Alps is divided over several tributaries in the WA sub-basin, whereas in EA, it is directly connected to the main river channel. The more immediate response of discharge to snowmelt in EA can explain the higher correlations between the *S* index and low flows in this sub-basin.

Main. The general correlation patterns for the snow-dominated Alpine sub-basins and the downstream rainfed sub-basins are assumed to be different. This assumption is confirmed by comparing the correlation maps of the two groups of sub-basins. We only present the results for Main, as the correlation maps of the rainfed sub-basins are very similar (see Appendix). Figure 10 shows the correlations between low flows and indicators for the Main sub-basin. All preselected indicators have very

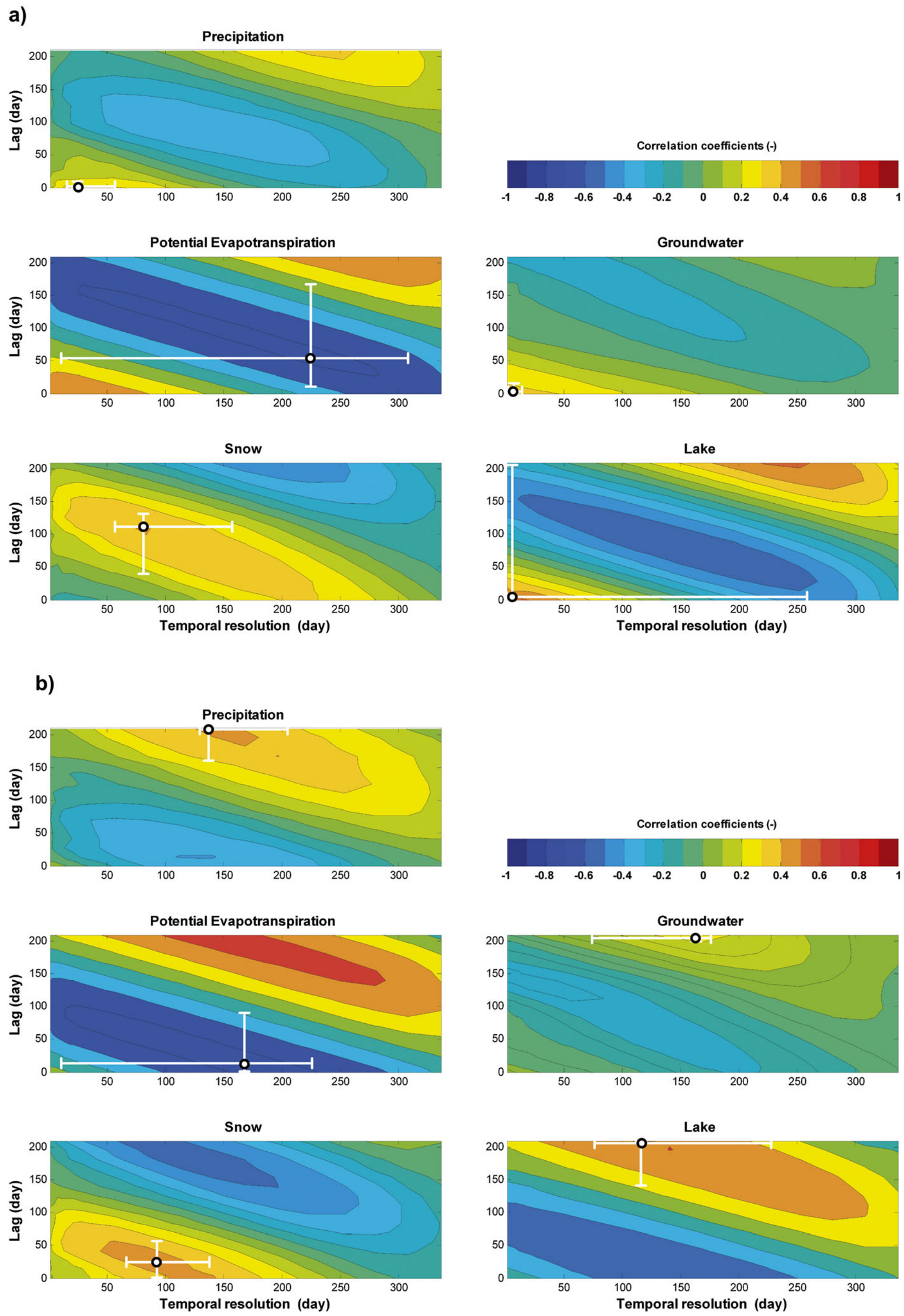

Figure 9. Cross correlation coefficients between low flows in the West Alpine sub-basin and preselected indicators as a function of lag and temporal resolution (days): a) low flows with a temporal resolution of three days and a lead time of 14 days; b) low flows with a temporal resolution of 7 days and a lead time of 90 days

similar maximum correlations for lead times of 14 and 90 days. The *P* index gives slightly higher correlations than the *PET* index for both lead times. Furthermore, the relative importance of the *P* index is also higher than that of the *G* index for forecasts with a lead time of 90 days, showing the importance of precipitation for this sub-basin.

Large lags (around 3 months) and temporal resolutions (around 8 months) are appropriate for the *P* index for forecasts with a lead time of 14 days. This result is in line with recent studies on the neighbouring rainfed Meuse basin, where low flows occur at the end of the summer and beginning of the autumn and depend on the amount of the preceding winter half year precipitation and also the preceding summer half year precipitation (De Wit *et al*., 2007; Booij and De Wit, 2010). The uncertainty over the appropriate lag for the *P* index is high due to the uncertainty over rainfall events. The *P* index averaged over a period of 5 months or longer shows similar correlations with low flows in the Main sub-basin. Due to the rainfed characteristic of the sub-basin, low flow occurrence in the Main sub-basin is not as persistent as it is in the Alpine sub-basins. Therefore, forecasting low flows can be more difficult than that for the sub-basins with high persistence.

Small lags (7 days) and large temporal resolutions (around 3 months) for the *PET* index are appropriate for

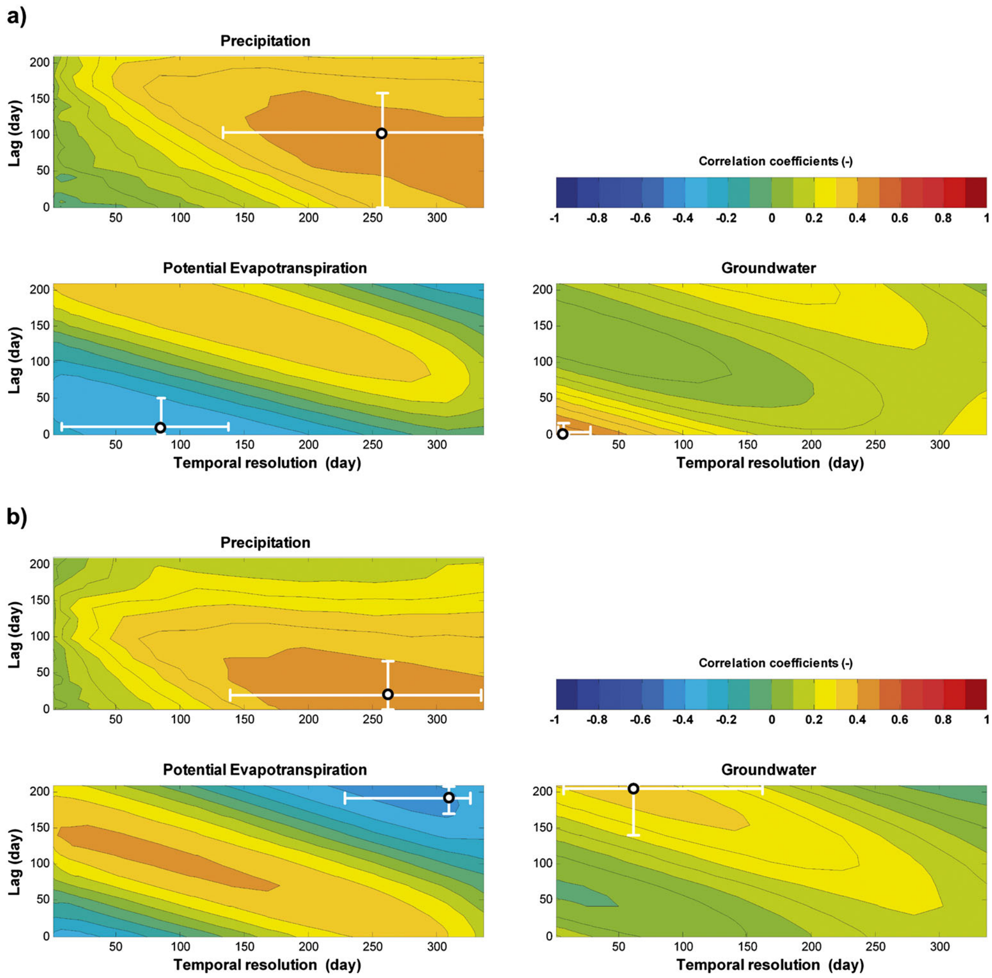

Figure 10. Cross correlation coefficients between low flows in the Main sub-basin and preselected indicators as a function of lag and temporal resolution (days): a) low flows with a temporal resolution of 3 days and a lead time of 14 days; b) low flows with a temporal resolution of 7 days and a lead time of 90 days

forecasts with a lead time of 14 days. In other words, for a lead time of 14 days, the potential evapotranspiration in the preceding 3 months, such as June, July and August, is important in issuing a low flow forecast in September. The appropriate lag and temporal resolution are assumed to be reasonable for such a medium scale rainfed sub-basin, where the summers can be dry.

Small lags (zero days) and daily temporal resolution for the *G* index are appropriate for forecasts with a lead time of 14 days. The maximum correlation between groundwater and low flows is higher than for all other sub-basins (see Figure 10a), possibly due to the existence of large aquifers (Middelkoop and Van Haselen, 1999; Belz, 2010).

For forecasts with a lead time of 90 days, small lags (14 days) and large temporal resolutions (about 8 months) are appropriate for the *P* index. Obviously, the appropriate lag for this index is shortened due to the additional lag of 76 days. For the *PET* index, the aforementioned effect of the annual hydrological cycle should be ignored, and small lags (7 days) with large temporal resolutions (around 3 months) should be used as appropriate temporal scales for forecasts with a lead time of 90 days (see Figure 10b).

Middle Rhine. The MR and LR sub-basins have a mixed discharge regime as it originates from both Alpine and rainfed sub-basins. The daily-generated discharge series contain negative values, even after applying a lag to account for the travel time of the discharge wave. This is possibly due to damming, mining, storage changes and other anthropogenic effects (Harris, 1946; Hüffmeyer *et al*., 2009; Belz, 2010). Moreover, given the large surface areas of these sub-basins, the annual discharge generation is relatively low.

The MR sub-basin is located in the middle part of the Rhine basin, covering approximately 25% of the total basin area. Therefore, the *PET* index is an important low flow indicator for forecasts with lead times of 14 and 90 days. Similarly, we found high correlations between the *G* index and low flows for forecasts with a lead time of 14 days (Figure 11). The high correlations for the *PET* index together with the low annual discharge generation rate show the significant role of *PET* in the water balance of the sub-basin.

Small lags (zero days) and large temporal scales (around 2 months) for the *PET* index are appropriate for forecasts with a lead time of 14 days. This means that the potential evapotranspiration amount in the preceding 2

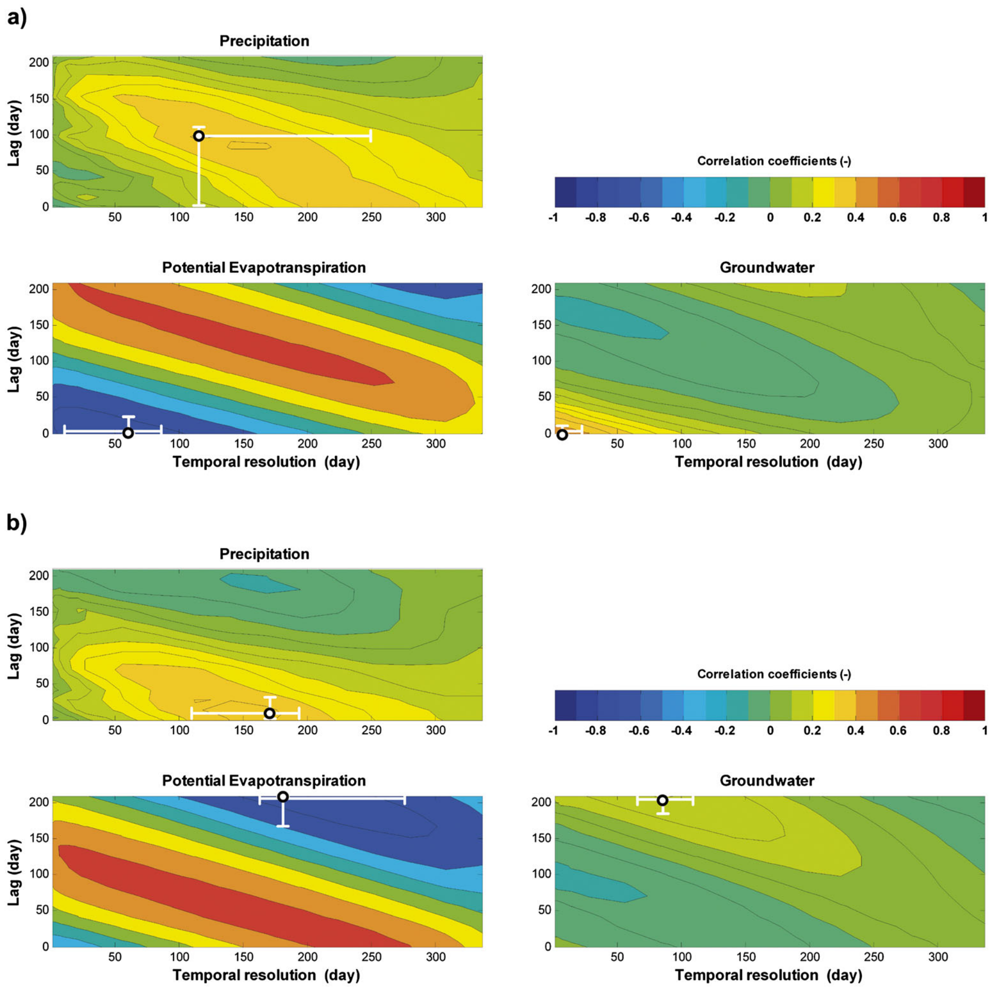

Figure 11. Cross correlation coefficients between low flows in the Middle Rhine sub-basin and preselected indicators as a function of lag and temporal resolution (days): a) low flows with a temporal resolution of 3 days and a lead time of 14 days; b) low flows with a temporal resolution of 7 days and a lead time of 90 days

months with a lag of zero days results in the highest correlation with low flows for a lead time of 14 days. On the other hand, small lags (zero days) and daily temporal resolution for the *G* index are appropriate for forecasts with lead times of 14 and 90 days. It can be concluded that the preceding daily groundwater levels are relevant for low flows in the MR sub-basin. The effect of the annual hydrological cycle on the correlations for the *PET* and *G* indices should be ignored, and the aforementioned appropriate temporal scales for these low flow indicators should be used for forecasts with a lead time of 90 days. Although the groundwater levels do not change quickly, groundwater can be the only storage sustaining low flows in a dry period, in particular in rainfed sub-basins.

Lower Rhine. Figure 12 shows the correlation coefficients between low flows and indicators for the LR sub-basin. The correlations are relatively low compared to upstream sub-basins. The *PET* and *G* indices are the most important low flow indicators here. The annually generated discharge is about 273 mm. Large lags (around 7 months) and temporal resolutions (around 10 months) for the *PET* index are appropriate for forecasts with a lead time of 14 days, while small lags (zero days) and daily temporal resolution for the *G* index are appropriate for forecasts with lead times of 14 and 90 days. The annual hydrological cycle effect on the *G* index should be ignored (Figure 12b).

Overall results agree with the general theory that the discharge response of a river basin is closely related to the preceding precipitation averages over several months. This is due to the fact that precipitation deficits over a long period can lead to a significant decrease in discharges (Vicente-Serrano and López-Moreno, 2005; De Wit *et al*., 2007). Zaidman *et al*. (2001) found strong correlations between low flows and average precipitation deficits over the preceding 2 to 4 months in northwest Europe. They indicated that the catchment geology plays an important role in low flows. We also found strong correlations between groundwater storage and low flows in most sub-basins. We did not analyse the correlations between atmospheric and oceanic indicators, such as the North Atlantic Oscillation index and the El Nino Southern Oscillation index, and low flows. Recent work has suggested that these indices did not increase the

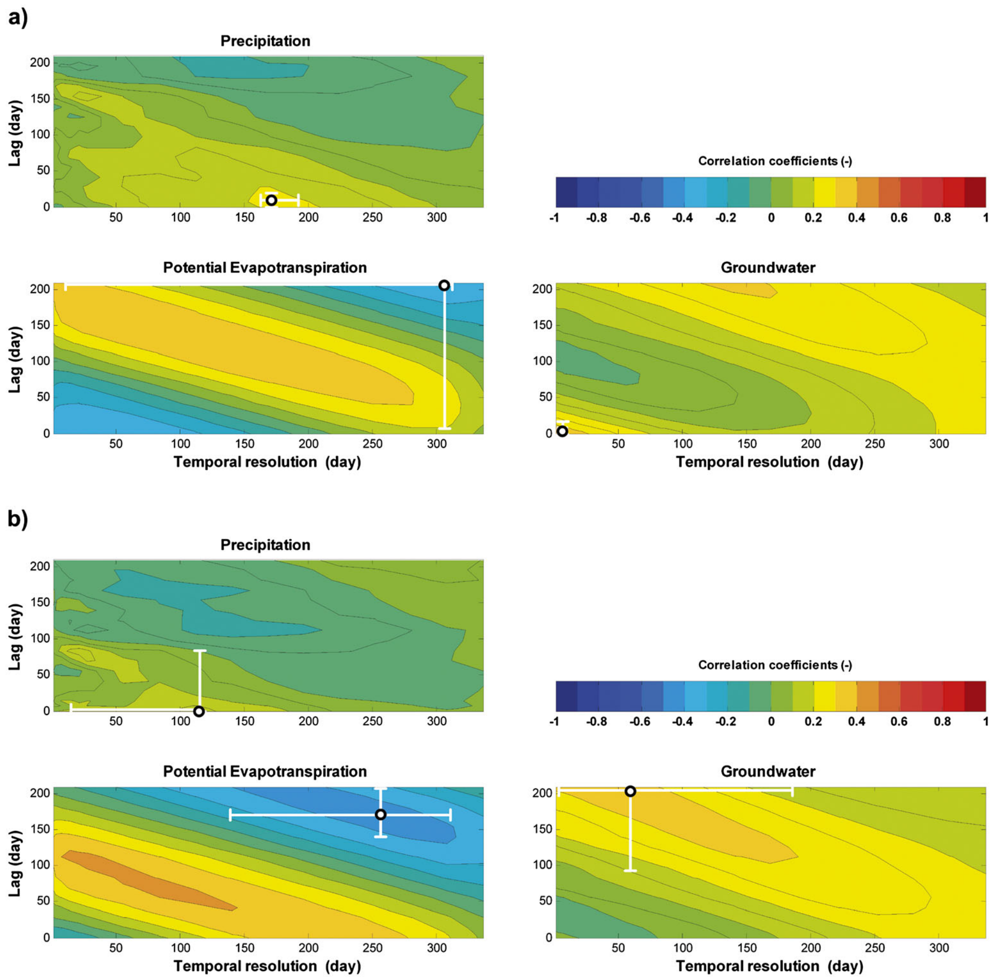

Figure 12. Cross correlation coefficients between low flows in the Lower Rhine sub-basin and preselected indicators as a function of lag and temporal resolution (days): a) low flows with a temporal resolution of 3 days and a lead time of 14 days; b) low flows with a temporal resolution of 7 days and a lead time of 90 days

ability to predict of summer discharge (low flows) and water temperature (Rutten *et al*., 2008).

CONCLUSIONS

This study investigated the use of sub-basin averaged standard indices and correlation analysis to characterise low flows in the River Rhine basin for an ultimate goal of low flow forecasting. Correlation analysis is not new in low flow hydrology, as it has been applied in a number of river basins (Wedgbrow *et al*., 2002; Vicente-Serrano and López-Moreno, 2005; Rutten *et al*., 2008). However, to our knowledge this is the first study applying correlation analysis to low flows in the River Rhine.

This study presented a correlation analysis, to assess the relative importance of low flow indicators for the Rhine and to identify their appropriate lags and temporal resolutions. The most important indicators in the Alpine sub-basins for forecasts with a lead time of 14 days are potential evapotranspiration and lake levels. In the other sub-basins, groundwater levels and potential evapotranspiration are relevant for low flows. Similarly, the most important indicators for forecasts with a lead time of 90 days are potential evapotranspiration, lake levels and snow depths for the Alpine sub-basins, whereas in the other sub-basins, the most important indicators are potential evapotranspiration and precipitation or groundwater.

Overall, small lags and temporal resolutions are appropriate for lake levels and groundwater in the sub-basins for forecasts with lead times of 14 and 90 days, while large lags and temporal resolutions are appropriate for the *P*, *PET* and *S* indices. The uncertainty over the appropriate lags and temporal resolutions was estimated for each indicator as well. As a result, we found a large uncertainty range around the maximum correlation points for most low flow indicators. In all sub-basins, the greatest uncertainties are found for the *PET* index. Lake levels and the *G* index show a small uncertainty range around the maximum correlation point.

The identified lags and temporal resolutions will be instrumentally useful in creating operational low flow forecast models for the River Rhine with lead times of 14 and 90 days. Additionally, understanding the low flow mechanisms and subsequent storage responses should aid the selection of appropriate models and the choice of proper temporal scales. Anticipating low flows would allow the making of more strategic decisions for river functions (e.g. navigation, cooling water supply) affected by low flows, as more low flows as well as extreme flood peaks are expected in the future (Hurkmans *et al.*, 2010). The framework presented in this study can be applied to all discharge regimes. Other methods, such as wavelet coherence analysis and chaotic correlation dimension methods, could also be used to identify dominant scales and the number of indicators in each sub-basin. Such methods are the basis for our on-going research.

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APPENDIX A: FIGURES FOR THE OTHER RAINFED SUB-BASINS

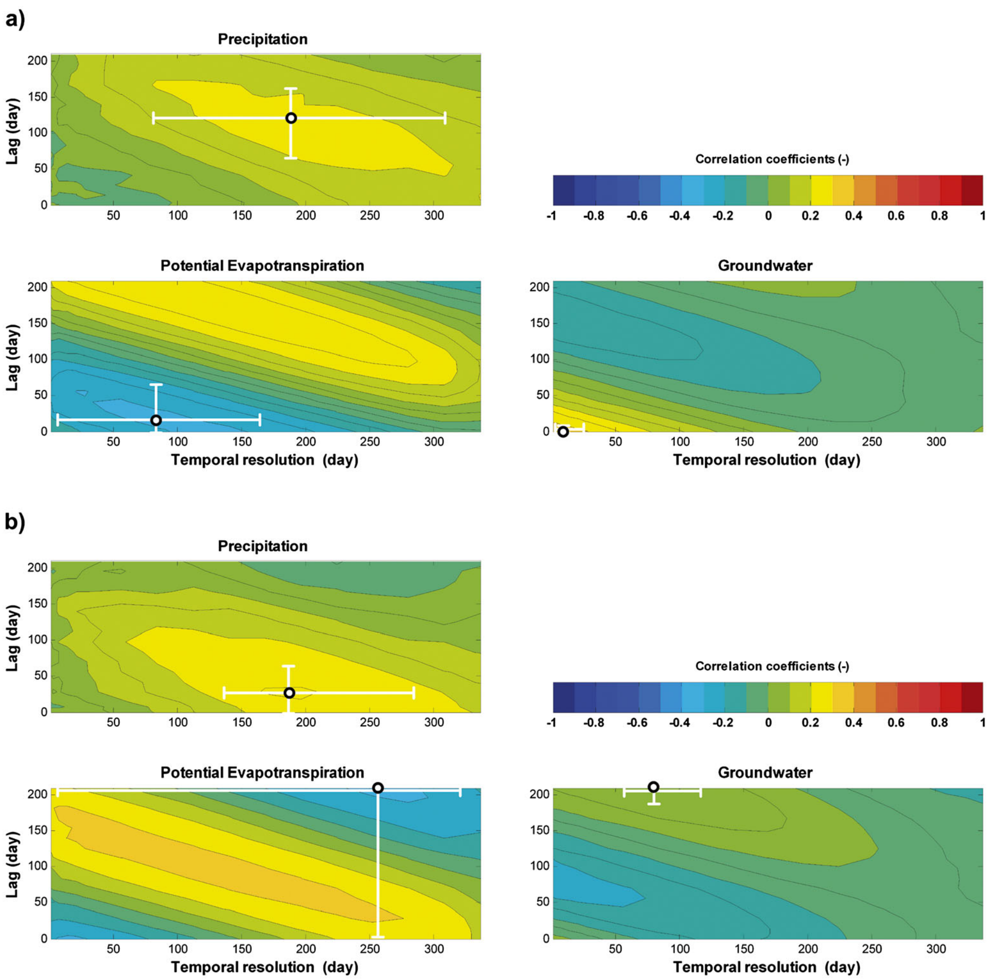

Figure 13. Cross correlation coefficients between low flows in the Neckar sub-basin and preselected indicators as a function of lag and temporal resolution (days): a) low flows with a temporal resolution of 3 days and a lead time of 14 days; b) low flows with a temporal resolution of 7 days and a lead time of 90 days

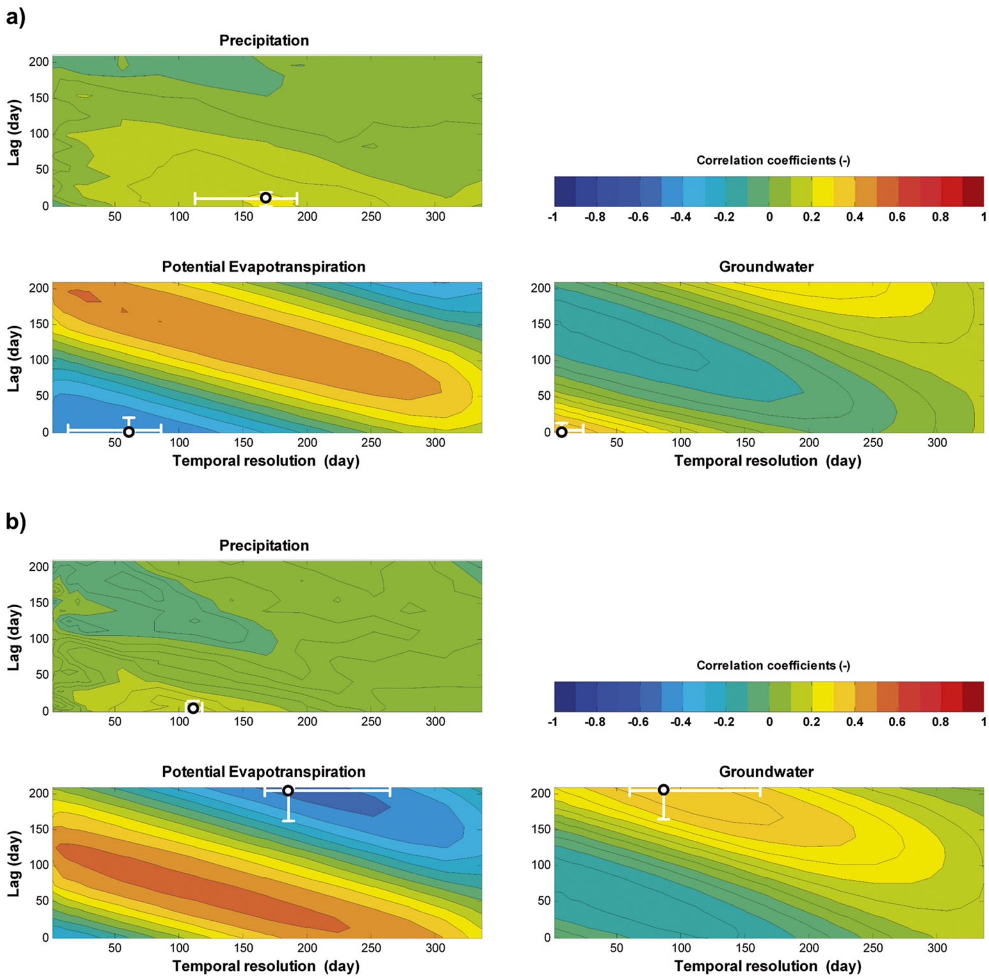

Figure 14. Cross correlation coefficients between low flows in the Moselle sub-basin and preselected indicators as a function of lag and temporal resolution (days): a) low flows with a temporal resolution of 3 days and a lead time of 14 days; b) low flows with a temporal resolution of 7 days and a lead time of 90 days

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