Detection of changes in streamflow series in western Europe over 1901–2000


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Abstract Streamflow processes of 12 rivers in western Europe are investigated for trend and nonstationarity in the full 100-year period in the 20th century. Trend analyses with Mann–Kendall test show that there is no trend in annual mean discharges. Only three annual maximum flow series exhibit significant trends (Rhine and Moselle, upward; Rhone, downward). There are two minimum flow series exhibiting significant downward trend (Maas and Thames) and five exhibiting upward trend (Danube, Elbe, Weser, Reuss and Rhone). Monthly flow series are examined with seasonal Kendall test. A significant downward trend is observed in the monthly flow series of Maas, whereas a significant upward trend is observed in the monthly flow series of Rhone. Meanwhile, significant heterogeneity in trends among different months is observed in three Alpine rivers (Inn, Reuss and Rhone). ADF and KPSS tests which originate from econometrics are introduced to test for nonstationarity in streamflow series at three characteristic timescales. All annual mean discharge series and most monthly mean discharge series appear to be stationary. But only 2 out of the 12 daily series are statistically stationary.

Keywords ADF test; KPSS test; Mann–Kendall test; stationarity; streamflow time series; trend

Introduction
The assumption of stationarity of hydrological processes of river stage or discharge is central to most flood risk analysis and flood defence system designs. From the view of a hydrological modeller, it is an important task to determine if there is the existence of any trend or other forms of nonstationarity in the data and how to achieve stationarity when the data is nonstationary. On the other hand, detecting the trend and stationarity in a hydrological time series may help us to understand the possible links between hydrological processes and global environment changes. The possible effects of global warming on water resources have been the topic of many recent studies (e.g., Lettenmaier et al., 1999; Jain and Lall, 2001).

Many studies have been carried out to detect changes in the streamflow processes and other hydrological processes globally, e.g., in Canada (Zhang et al., 2001; Burn and Hag Elmur, 2002), United States (Lins and Slack, 1999; McCabe and Wolock, 2002), as well as in some European countries. Robson (2002) found no statistical evidence of a long-term trend in flooding in UK over the last 80–120 years. van Gelder et al. (2000) found no evidence of an upward trend in annual average discharges of the Rhine River at Lobith. De Wit et al. (2001) investigated the discharge records of the River Meuse for the period 1911 to 1998, and found that the average annual and seasonal discharges have hardly changed over the last century. However, the maximum daily winter discharges seem to have increased, whereas the minimum summer discharges seem to have decreased. Mudelsee et al. (2003) found a decrease in winter flood occurrence in both the Elb and Oder rivers in central Europe, while summer floods show no trend for the past 80 to 150 years. Nobilis and Lorenz (1997) found no general significant linear long-term...
trend in yearly maxima of discharges for the whole of Austria for the period 1952 to 1991. Lindström and Bergström (2004) found that the estimated runoff in Sweden over the 20th century increased by about 4% on average, but the trend was not statistically significant. At the same time, some significant trends have been detected on a local scale. Mansell (1997) showed an increase in streamflow in four catchments of small to medium size in western Scotland over the period 1964 to 1994. Pfister et al. (2000) analyzed daily rainfall data from 1954 to 1996 in the stations of Luxembourg city and Belvaux, and showed an increase in winter rainfall intensity and duration, which has induced a significant increase in the winter maximum daily storm flow in the Alzette River basin in Luxembourg since the 1970s. Caspary (2000) analyzed time series of discharge in four rivers in Germany and found a marked recent increase in the amplitude of floods. Kundzewicz et al. (2004) analysed 70 maximum annual flow series in Europe, and found that 20 showed significant changes (11 increase and 9 decrease) at 90% level.

Although these studies have explored the trends of hydrological processes for some local regions in Europe, their extrapolation to a regional or continental scale remains uncertain, because the factors acting on streamflow trends on a basin scale are not necessarily similar to those acting on a regional or continental scale (Pfister et al., 2000). Additionally, while we find some remarkable interannual-to-interdecadal variations in a hydrological sequence for some periods, it is very difficult to detect whether such variations are significant or whether it is part of an oscillation (Matalas, 1997). Consequently, there has been no conclusive and general proof as to how climate change affects flood behaviour, in the light of data observed so far (Kundzewicz et al., 2004); more study on this issue is needed. In this paper, long-term variations in streamflow series in western Europe are analysed for the whole 20th century. The trend of 12 rivers in western Europe is investigated with the non-parametric Mann–Kendall method, and the stationarity is examined with the Dickey-Fuller unit root test (Dickey and Fuller, 1979) and KPSS test (Kwiatkowski et al., 1992), which originate from econometrics.

Data used
To investigate possible changes in streamflow processes in western Europe over the 20th century, we choose streamflow processes of 12 major rivers, which basically temporally span the whole century and are spatially evenly located in western Europe. The descriptions of the 12 streamflow processes are listed in Table 1. Daily discharge data are provided by the Global Runoff Data Center (GRDC), which are available on the website http://grdc.bafg.de/. The daily data are aggregated to monthly and annual data by taking the average of each month and each calendar year. The annual maximum daily average discharge and minimum daily average discharge as well as their corresponding timing are obtained according to the water year of each streamflow process.

Trend analysis
A rank-based nonparametric method, the Mann–Kendall’s test, is used in the study to test for the trends in annual and monthly series. The non-parametric trend detection method has the advantage over parametric methods of its less sensitivity to outliers (extremes). We will first test for trends in annual series so as to obtain an overall view of the changes in streamflow processes, then test for trend in monthly streamflow series so as to have an image of any seasonal patterns in the changes.

Trend test for annual series
Mann–Kendall test. Kendall (1938) proposed a measure $\tau$ to measure the strength of the monotonic relationship between $x$ and $y$. Mann (1945) suggested using the test for
<table>
<thead>
<tr>
<th>GRDC_No</th>
<th>River</th>
<th>Station</th>
<th>Country</th>
<th>Period</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Upstream area (km²)</th>
<th>Elevation (m)</th>
<th>Mean discharge (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6335060</td>
<td>Rhine</td>
<td>Cologne</td>
<td>Germany</td>
<td>1901–2000</td>
<td>50.937</td>
<td>6.963</td>
<td>144,232</td>
<td>35</td>
<td>2,094</td>
</tr>
<tr>
<td>6335301</td>
<td>Main</td>
<td>Schweinfurt</td>
<td>Germany</td>
<td>1901–2000</td>
<td>50.031</td>
<td>10.221</td>
<td>12,715</td>
<td>201</td>
<td>108</td>
</tr>
<tr>
<td>6336050</td>
<td>Moselle</td>
<td>Cochem</td>
<td>Germany</td>
<td>1901–2000</td>
<td>50.143</td>
<td>7.168</td>
<td>27,088</td>
<td>77</td>
<td>318</td>
</tr>
<tr>
<td>6337100</td>
<td>Weser</td>
<td>Vlotho</td>
<td>Germany</td>
<td>1901–2000</td>
<td>52.176</td>
<td>8.862</td>
<td>17,618</td>
<td>42</td>
<td>172</td>
</tr>
<tr>
<td>6337502</td>
<td>Aller</td>
<td>Celle</td>
<td>Germany</td>
<td>1901–2000</td>
<td>52.622</td>
<td>10.063</td>
<td>4,374</td>
<td>32</td>
<td>27</td>
</tr>
<tr>
<td>6340120</td>
<td>Elbe</td>
<td>Dresden</td>
<td>Germany</td>
<td>1901–2000</td>
<td>51.06</td>
<td>13.739</td>
<td>53,096</td>
<td>103</td>
<td>318</td>
</tr>
<tr>
<td>6421500</td>
<td>Maas</td>
<td>Borgharen</td>
<td>Netherlands</td>
<td>1911–2000</td>
<td>50.87</td>
<td>5.72</td>
<td>21,300</td>
<td>40</td>
<td>246</td>
</tr>
<tr>
<td>6607650</td>
<td>Thames</td>
<td>Kingston</td>
<td>UK</td>
<td>1901–2000</td>
<td>51.8</td>
<td>–0.8</td>
<td>9,948</td>
<td>–</td>
<td>66</td>
</tr>
<tr>
<td>6935310</td>
<td>Reuss</td>
<td>Mellingen</td>
<td>Switzerland</td>
<td>1904–2000</td>
<td>47.39</td>
<td>8.25</td>
<td>3,382</td>
<td>–</td>
<td>139</td>
</tr>
<tr>
<td>6939200</td>
<td>Rhone</td>
<td>Porte Du Scex</td>
<td>Switzerland</td>
<td>1905–2000</td>
<td>46.35</td>
<td>6.89</td>
<td>5,220</td>
<td>–</td>
<td>343</td>
</tr>
</tbody>
</table>
significance of Kendall’s \( \tau \), where one of the variables is time as a test for trend. The test is well known as Mann–Kendall’s test (referred to as MK test hereafter), which is powerful for uncovering deterministic trends. It has been found that positive serial correlation inflates the variance of the MK statistic \( S \) and hence increases the possibility of rejecting the null hypothesis of no trend (von Storch, 1995). In order to reduce the impact of serial correlation, it is common to prewhiten the time series by removing serial correlation from the series through \( y_t = x_t - \phi x_{t-1} \), where \( y_t \) is the prewhitened series value, \( x_t \) is the original time series value, and \( \phi \) is the estimated lag 1 serial correlation coefficient.

**Mann–Kendall test results.** The trend of the annual maximum and minimum daily average discharge as well as their timing are analyzed with MK test. Because annual mean discharge sequences usually exhibit serial dependence, therefore, they are prewhiten. But annual maxima and minima series are basically uncorrelated, so prewhitening is not necessary. The MK test results are displayed in Table 2.

Results of this analysis indicate no significant increasing or decreasing trends in annual mean discharges of all the rivers. However, trend is present in some annual maximum and minimum flows. Out of 12 maximum flow series, two series (i.e., Rhine and Moselle) exhibit significant increases, one series (Rhone) shows downward trend at a 95% significance level. The positive trend in annual maxima of Rhine at Cologne was also observed by Engel (1997). In contrast, seven minimum flow series exhibit significant downward (Maas and Thames) or upward trend (Weser, Elbe, Danube, Reuss and Rhone) at the level of 95%. The timing of annual maxima exhibits no significant change, but the timing of annual minima at five sites has significant changes. The occurrence of minimum flows of the Rhone gets earlier, whereas the minimum flows of Main, Weser, Aller and Maas come later.

A close visual inspection at the annual mean series and maxima series reveals the following: the annual maxima of both Rhine and Moselle probably experienced a step-change in the mid-1970s; similarly, the annual means of both Rhine and Moselle probably also experienced a step-change in the mid-1970s, although such step-changes are not statistically significant; the downward trend in annual maxima of Rhone happened after the 1940s; although not statistically significant, the slight downward trends in the annual maxima of Elbe and Inn are discernible, especially for the first half of the 20th century.

<table>
<thead>
<tr>
<th>River</th>
<th>Annual mean</th>
<th>Annual maxima</th>
<th>Timing of maxima</th>
<th>Annual minima</th>
<th>Timing of minima</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \tau )</td>
<td>( p )-value</td>
<td>( \tau )</td>
<td>( p )-value</td>
<td>( \tau )</td>
</tr>
<tr>
<td>Rhine</td>
<td>0.034</td>
<td>0.620</td>
<td>0.165</td>
<td>0.015</td>
<td>-0.045</td>
</tr>
<tr>
<td>Main</td>
<td>0.014</td>
<td>0.837</td>
<td>0.006</td>
<td>0.929</td>
<td>-0.053</td>
</tr>
<tr>
<td>Moselle</td>
<td>0.056</td>
<td>0.414</td>
<td>0.183</td>
<td>0.007</td>
<td>0.047</td>
</tr>
<tr>
<td>Weser</td>
<td>0.022</td>
<td>0.749</td>
<td>-0.045</td>
<td>0.512</td>
<td>0.099</td>
</tr>
<tr>
<td>Aller</td>
<td>0.017</td>
<td>0.804</td>
<td>-0.023</td>
<td>0.732</td>
<td>0.071</td>
</tr>
<tr>
<td>Elbe</td>
<td>-0.008</td>
<td>0.904</td>
<td>-0.039</td>
<td>0.569</td>
<td>0.037</td>
</tr>
<tr>
<td>Danube</td>
<td>0.016</td>
<td>0.814</td>
<td>0.095</td>
<td>0.164</td>
<td>0.003</td>
</tr>
<tr>
<td>Inn</td>
<td>0.000</td>
<td>1.000</td>
<td>-0.070</td>
<td>0.303</td>
<td>-0.071</td>
</tr>
<tr>
<td>Maas</td>
<td>0.014</td>
<td>0.851</td>
<td>0.095</td>
<td>0.190</td>
<td>0.000</td>
</tr>
<tr>
<td>Thames</td>
<td>-0.002</td>
<td>0.976</td>
<td>0.007</td>
<td>0.919</td>
<td>-0.106</td>
</tr>
<tr>
<td>Reuss</td>
<td>0.002</td>
<td>0.982</td>
<td>0.098</td>
<td>0.154</td>
<td>-0.026</td>
</tr>
<tr>
<td>Rhone</td>
<td>0.023</td>
<td>0.743</td>
<td>-0.307</td>
<td>0.000</td>
<td>-0.057</td>
</tr>
</tbody>
</table>

Null hypothesis: \( \tau = 0 \). The values in bold indicate that the null hypothesis is rejected at a 5% significance level.
century; an upward trend in the annual mean series is also discernible; nevertheless it is not statistically significant.

Taking a close visual inspection at the annual minima series, we cannot find consistent changing patterns among different rivers, but some more details are revealed: the annual minima of Danube, Elbe had an upward step-change around the mid-1960s; the annual minima of Elbe experienced a significant change in the 1940s, i.e., decrease before 1940s, then significant increase afterwards; the upward trend in the annual minima of the Rhine occurred only in the second half of the 20th century; while the annual minima of Maas decrease, their variability also decreases; the minima of Reuss also experienced an upward step-change in the 1920s; the minima of Rhone started to rise from the beginning of the 20th century, but the rising is not significant after the 1960s; the minima of Thames only show significant downward trend after the end of the 1980s, whereas for the period before 1995 we can even detect a upward trend; the rising of the minima of Weser appears to start from the 1910s.

Trend test for monthly series
To detect possible changes in more detail, we need to examine the monthly flow series. Monthly streamflows usually exhibit strong seasonality. A modification of Kendall’s test, referred to as the seasonal Kendall test (Hirsch et al., 1982; Hirsch and Slack, 1984), is used here.

Seasonal Kendall test. The seasonal Kendall test accounts for seasonality by computing the MK test on each of \( p \) seasons separately, and then combining the results. Seasonal Kendall test is appropriate for testing for trend in each season when the trend is always in the same direction across all seasons. However, the trend may have different directions in different seasons. van Belle and Hughes (1984) suggested a test for detecting heterogeneity in trends among different seasons.

Seasonal Kendall test results. The 12 monthly streamflow processes are tested for trend with the seasonal Kendall test which allows for the serial dependence. And the homogeneity of trend is also tested. The results are shown in Table 3. The results give the same conclusion as that given by the MK test for annual series (i.e., no trend is observed), except for the monthly series of Maas and Rhone. The monthly flows of Maas exhibit declining trend, whereas those of Rhone exhibit upward trend at the 95% significance level. Meanwhile, it is found that there is significant trend heterogeneity in monthly streamflows of three rivers, i.e., Inn, Reuss and Rhone, all of which mostly flow within the Alpine region. Consequently, we further investigate the trend of average flows of each month for these three months. The results are shown in Table 4. A clear seasonal pattern is revealed, that is, monthly flows in summer (June to September) decrease, whereas in the winter half year (November to March) they increase. This pattern is most obvious for the Rhone River, which is fully located in the Alps.

Stationarity test
While the purpose of trend tests is to determine whether the values of a series have a general increase or decrease with the time increase, the purpose of stationarity tests is to determine whether the mean values and variances of a series vary with time. There are roughly two groups of methods for testing stationarity. The first group are based on ideas of analyzing the statistical differences of different segments of the time series (e.g. Chen and Rao, 2002). If the observed variations in a certain parameter of different segments are found to be significant, that is, outside the expected statistical fluctuations, the time
Table 3: Seasonal Kendall tests and heterogeneity tests on monthly series

<table>
<thead>
<tr>
<th></th>
<th>Rhine</th>
<th>Main</th>
<th>Moselle</th>
<th>Weser</th>
<th>Aller</th>
<th>Elbe</th>
<th>Danube</th>
<th>Inn</th>
<th>Maas</th>
<th>Thames</th>
<th>Reuss</th>
<th>Rhone</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-value of trend test</td>
<td>0.293</td>
<td>0.171</td>
<td>0.326</td>
<td>0.226</td>
<td>0.330</td>
<td>0.998</td>
<td>0.517</td>
<td>0.206</td>
<td>0.020</td>
<td>0.092</td>
<td>0.179</td>
<td>0.000</td>
</tr>
<tr>
<td>p-value of heterogeneity test</td>
<td>0.703</td>
<td>0.233</td>
<td>0.485</td>
<td>0.357</td>
<td>0.069</td>
<td>0.967</td>
<td>0.430</td>
<td>0.000</td>
<td>0.171</td>
<td>0.623</td>
<td>0.001</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Null hypothesis for trend test: $r = 0$
Null hypothesis for trend homogeneity test: $r$ of all seasons are equal to $0$
Table 4 Mann–Kendall tests on flows of each month for monthly series

<table>
<thead>
<tr>
<th></th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inn</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau$</td>
<td>0.223</td>
<td>0.313</td>
<td>0.274</td>
<td>0.060</td>
<td>-0.049</td>
<td>-0.183</td>
<td>-0.097</td>
<td>-0.131</td>
<td>-0.137</td>
<td>0.004</td>
<td>0.084</td>
<td>0.187</td>
</tr>
<tr>
<td>$p$-value</td>
<td><strong>0.001</strong></td>
<td><strong>0.000</strong></td>
<td><strong>0.000</strong></td>
<td>0.378</td>
<td><strong>0.007</strong></td>
<td>0.155</td>
<td>0.055</td>
<td><strong>0.044</strong></td>
<td>0.955</td>
<td>0.218</td>
<td>0.006</td>
<td></td>
</tr>
<tr>
<td>Reuss</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau$</td>
<td>0.123</td>
<td>0.213</td>
<td>0.229</td>
<td>0.085</td>
<td>-0.010</td>
<td>-0.086</td>
<td>-0.058</td>
<td>-0.107</td>
<td>-0.054</td>
<td>0.000</td>
<td>0.051</td>
<td>0.218</td>
</tr>
<tr>
<td>$p$-value</td>
<td>0.074</td>
<td><strong>0.002</strong></td>
<td><strong>0.001</strong></td>
<td>0.218</td>
<td>0.891</td>
<td>0.213</td>
<td>0.402</td>
<td>0.121</td>
<td>0.438</td>
<td>0.998</td>
<td>0.460</td>
<td><strong>0.002</strong></td>
</tr>
<tr>
<td>Rhone</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$\tau$</td>
<td>0.632</td>
<td>0.689</td>
<td>0.649</td>
<td>0.429</td>
<td>0.028</td>
<td>-0.263</td>
<td>-0.350</td>
<td>-0.406</td>
<td>-0.119</td>
<td>0.325</td>
<td>0.533</td>
<td>0.607</td>
</tr>
<tr>
<td>$p$-value</td>
<td><strong>0.000</strong></td>
<td><strong>0.000</strong></td>
<td><strong>0.000</strong></td>
<td><strong>0.000</strong></td>
<td>0.690</td>
<td><strong>0.000</strong></td>
<td><strong>0.000</strong></td>
<td><strong>0.000</strong></td>
<td>0.087</td>
<td><strong>0.000</strong></td>
<td><strong>0.000</strong></td>
<td><strong>0.000</strong></td>
</tr>
</tbody>
</table>
series is regarded as nonstationary. Another group of stationarity tests are based on statistics for the full sequence. We adopt the second approach here.

Methods of testing stationarity. The stationarity test based on statistics for the full sequence is carried out with two methods in the present study. One is the augmented Dickey–Fuller (ADF) unit root test first proposed by Dickey and Fuller (1979) and modified by Said and Dickey (1984), which tests for the null hypothesis of the presence of unit roots in a series (difference stationarity); another is KPSS test proposed by Kwiatkowski et al. (1992), which tests for the null hypothesis of stationarity around a deterministic trend (trend stationarity) and the null hypothesis of stationarity around a fixed level (level stationarity). If a process is not level stationary but trend stationary, it indicates that the process may be decomposed into a trend component and a stationary component. The ADF test and KPSS test have been used to test for stationarity in streamflow series by Wang et al. (2005).

Stationarity test results. Because on one hand both ADF and KPSS tests are based on linear regression, which has the normal distribution assumption; on the other hand, log-transformation can convert exponential trend possibly present in the data into a linear trend, therefore, it is common to take logs of the data before applying ADF and KPSS tests (e.g. Gimeno et al., 1999). This pre-processing procedure is followed in this study. Because the daily streamflow series of the Maas River has several zero discharges, we add 0.5 to all the discharges before taking log-transformation. To eliminate possible impacts of seasonality present in the streamflow processes on the effectiveness of stationarity tests, besides log-transformation, data are also deseasonalized. Deseasonalization is performed by subtracting the seasonal (daily or monthly) mean values and dividing by seasonal standard deviations.

An important practical issue for the implementation of the ADF and KPSS tests is the specification of the truncation lag value $p$. The KPSS test statistics are fairly sensitive to the choice of $p$, and in fact for every series the value of the test statistic decreases as $p$ increases (Kwiatkowski et al., 1992). If $p$ is too small, then the remaining serial correlation in the errors will bias the test. If $p$ is too large, then the power of the test will suffer. Because the major concern when choosing an appropriate value of $p$ is to take into account the serial correlation in the time series data, thus in the present study, for daily and monthly series, we choose the value of $p$ according to the orders of fitted AR models which are determined with Akaike Information Criterion. For annual series, we choose $p = 1$.

The stationarity test results are given in Table 5. Most monthly (except for the Maas, Thames and Rhone) and all annual series appear to be significantly stationary, since we cannot accept the unit root hypothesis with ADF test at 1% significance level and cannot reject the trend stationarity hypothesis and level stationarity hypothesis with KPSS test at the 5% level. For Maas, Thames and Rhone, monthly streamflow process is trend stationary at significance level 2.5% or above, but not level stationary at 1% level. This indicates that there are weak trend components inside these monthly series, and the nonstationarity stems from the trend components. This is basically in agreement with the results of the seasonal Kendall test, which show that the monthly series of Maas and Rhone have trends at 95% level, whereas the monthly series of Thames has a trend at 90% level. Among the 12 daily flow series, only two series pass level stationarity test (Danube and Elbe) at significance level 5%. Other daily series are level non-stationary, because they either cannot pass the level stationarity test at 1% level, or just pass it at a very low significance level (1% for Rhine and Moselle). Among the ten level non-stationary series, only for the daily series of
Rhine gets earlier, whereas the minimum flows of Main, Weser, Aller and Maas come mum flow series exhibit significant trend (Rhine and Moselle, upward; Rhone, downward).

Annual minimum daily discharges and their timing are investigated with Mann–Kendall Streamflow series of twelve rivers, which temporally span the whole 20th century and are

<table>
<thead>
<tr>
<th>River</th>
<th>Timescale</th>
<th>Lag</th>
<th>KPSS level stationarity</th>
<th>KPSS trend stationarity</th>
<th>ADF unit roots</th>
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<td>statistic</td>
<td>p-value</td>
<td>statistic</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
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<td>6</td>
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<td>0.375 &lt; 0.01</td>
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<td>Moselle</td>
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<td>0.639 &gt; 0.01</td>
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<td>0.237 &lt; 0.01</td>
<td>−11.10</td>
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<td>Monthly</td>
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<td>0.517 &gt; 0.025</td>
<td>0.082 &gt; 0.1</td>
<td>−11.77</td>
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<tr>
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<td>Annual</td>
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<td>0.045 &gt; 0.1</td>
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<tr>
<td>Aller</td>
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<td>0.408 &lt; 0.01</td>
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<tr>
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<td>0.092 &gt; 0.1</td>
<td>0.090 &gt; 0.1</td>
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<tr>
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<td>0.040 &gt; 0.1</td>
<td>0.039 &gt; 0.1</td>
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<tr>
<td>Danube</td>
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<td>39</td>
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<td>0.180 &gt; 0.01</td>
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<tr>
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<td>Monthly</td>
<td>6</td>
<td>0.159 &gt; 0.1</td>
<td>0.069 &gt; 0.1</td>
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<tr>
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<td>0.037 &gt; 0.1</td>
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<td>Inn</td>
<td>Daily</td>
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<td>1.194 &lt; 0.01</td>
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<tr>
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<td>0.281 &gt; 0.1</td>
<td>0.135 &gt; 0.05</td>
<td>−6.76</td>
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<tr>
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<td>0.063 &gt; 0.1</td>
<td>0.047 &gt; 0.1</td>
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<td>Maas</td>
<td>Daily</td>
<td>45</td>
<td>3.016 &lt; 0.01</td>
<td>0.313 &lt; 0.01</td>
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<tr>
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<td>Monthly</td>
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<td>1.065 &lt; 0.01</td>
<td>0.160 &gt; 0.025</td>
<td>−11.00</td>
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<tr>
<td></td>
<td>Annual</td>
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<td>0.208 &gt; 0.1</td>
<td>0.077 &gt; 0.1</td>
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<td>Thames</td>
<td>Daily</td>
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<td>2.749 &lt; 0.01</td>
<td>0.360 &lt; 0.01</td>
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<td>0.119 &gt; 0.05</td>
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<td>Reuss</td>
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<td>0.307 &lt; 0.01</td>
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<td>0.112 &gt; 0.1</td>
<td>0.083 &gt; 0.1</td>
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<tr>
<td>Rhone</td>
<td>Daily</td>
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<td>10.364 &lt; 0.01</td>
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<td>0.246 &gt; 0.1</td>
<td>0.125 &gt; 0.05</td>
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</tbody>
</table>

Rhine we cannot reject the null hypothesis of trend stationary at 5% level. The result indicates that the non-stationarity in the daily series of Rhone mainly stems from the presence of trend, but the causes of nonstationarity in other level non-stationary series are not clear.

Conclusions
Streamflow series of twelve rivers, which temporally span the whole 20th century and are located at different geographical locations in western Europe, are investigated for long-term variations. The trend of annual mean discharges, annual maximum daily discharges, annual minimum daily discharges and their timing are investigated with Mann–Kendall test. Results show that there is no trend in annual mean discharge. Only three annual maximum flow series exhibit significant trend (Rhine and Moselle, upward; Rhone, downward). There are two minimum flow series exhibiting significant downward trend (Maas and Thames) and five exhibiting upward trend (Danube, Elbe, Weser, Reuss and Rhone). The timing of maximum flow exhibits no significant change, but the timing of minimum streamflow at 3 sites has significant change. The occurrence of minimum streamflow of the Rhone gets earlier, whereas the minimum flows of Main, Weser, Aller and Maas come

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later. Monthly flow series are examined with seasonal Kendall test. Significant downward trend is observed in the monthly flow series of Maas, whereas significant upward trend is observed in the monthly flow series of Rhone. Meanwhile, significant heterogeneity in trends among different months is observed in three Alpine rivers (Inn, Reuss and Rhone). For the three Alpine rivers, monthly flows in summer (June to September) decrease, whereas in the winter half year (November to March) they increase. This pattern is most obvious for the Rhone River, which is fully located in the Alps.

ADF test (Dickey and Fuller, 1979) and KPSS test (Kwiatkowski et al., 1992), which originate from econometrics, are introduced to test for nonstationarity in the streamflow processes. All annual streamflow series and most monthly streamflow series appear to be significantly stationary. The non-stationarity in three monthly series (Maas, Thames and Rhone) basically stem from the trends in these series, which are also detected with the seasonal Kendall test. But among the 12 daily flow series, only two series pass the level stationarity test (Danube and Elbe) at significance level 5%. Other daily series are level non-stationary, because they either cannot pass the level stationarity test at 1% level, or just pass at a very low significance level (1% for Rhine and Moselle). Among those ten level non-stationary series, only for the daily series of Rhone we cannot reject the null hypothesis of trend stationary at 5% level. The result indicates that the non-stationarity in the daily series of Rhone mainly stems from the presence of trend, but the causes of non-stationarity in other level non-stationary series are not clear.

Acknowledgements

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References


