Monthly and Seasonal Forecasting of Rhine water-levels and streamflow based on hydrologic, atmospheric and oceanic data

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Motivation

- 70% of the German waterways are of international relevance.
- River Rhine is one of the most frequented inland waterways in the world.
- 240 million tons per year are carried by inland waterway transport (IWT).
- Strengthening of the inland waterway transport is necessary to handle the continuing transport growth economically and ecologically sustainably.
- Low flows are the main hydrological impact on the reliability of IWT

<table>
<thead>
<tr>
<th>Country</th>
<th>Dry cargo fleet</th>
<th>Tanker fleet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Units (no.)</td>
<td>Capacity (tonnes)</td>
</tr>
<tr>
<td>The Netherlands</td>
<td>4,555</td>
<td>5,729,642</td>
</tr>
<tr>
<td>Belgium</td>
<td>1,102</td>
<td>1,502,987</td>
</tr>
<tr>
<td>Luxemburg</td>
<td>10</td>
<td>9,789</td>
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<tr>
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<td>1,240</td>
<td>1,028,815</td>
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<td>Switzerland</td>
<td>18</td>
<td>33,728</td>
</tr>
<tr>
<td>Total</td>
<td>8,623</td>
<td>10,340,125</td>
</tr>
</tbody>
</table>

*Source: CCNR and European Commission (2011)*
Objectives

- To identify large scale predictors for monthly and seasonal streamflow (low flow, mean flow and high flow) and water levels for the Rhine, Elbe, Weser and Danube rivers

- To develop a statistical algorithm for the monthly and seasonal prediction

- To test if the proposed methodology can be used as an operational system for monthly and seasonal outlook
Methodology I

- Detection of stable teleconnections: 21(31) – year window correlation between streamflow (NM7Q, MQ and HQ) and large scale factors (e.g. Sea Surface Temperature (SST), Temperature over land (TT), precipitation (PP)) → Stability map

- Define SST, TT, PP, SLP, RH, etc indices based on stability maps.

- EOF analysis of the indices.

- Comparison between PC1 and flow anomalies.

- Apply multiple regression to the indices identified based on the stability maps
  - Choose the optimal predictors based on stepwise and backward regression
Methodology II - Stability criteria

- more than 80% of the 31-yr windows are above 90% level \( (r = 0.24) \) - STABLE
- more than 80% of the 31-yr windows are above 80% level \( (r = 0.17) \) - STABLE
- more than 80% of the 31-yr windows are above 90% level \( (r = -0.24) \) - STABLE
- more than 80% of the 31-yr windows are above 80% level \( (r = -0.17) \) - STABLE
- less than 80% of the 31-yr windows are correlated - UNSTABLE
Non-stationarity issues

„Normal“ Correlation

SLP – Sea Level Pressure
SST – Sea Surface Temperature
TT - Air Temperature
PWC – Precipitable Water Content

Rhine MAM – Climate Variables DJF

„Stable“ Correlation
Data

- Monthly/daily streamflow data (NM7Q, MQ and HQ) measured at Neu Darchau (Elbe) and Kaub (Rhine), provided by Bfg.

- ERSST v4b (2°x2°) (1948-2017) (Smith and Reynolds, 2003)

- Precipitation (PP) and temperature (TT) data from the German Weather Service (DWD) (5km x 5km) (1948-2017).

- Sea level pressure (SLP), Geopotential Height, Relative Humidity, Soil Moisture, Ground Temperature, data (2.5 ° x 2.5 °) covering the period 1948-2015 from NCEP/NCAR data base (Compo et al., 2011).
Case study: Rhine River

Precipitation (mm/year)
- 0 - 200
- 201 - 400
- 401 - 600
- 601 - 650
- 651 - 700
- 701 - 750
- 751 - 800
- 801 - 850
- 851 - 900
- 901 - 1000
- 1001 - 1500
- 1501 - 2000
- 2001 - 2500
- 2501 - 3000
- 3001 - 3500

Monthly NM7Q Streamflow - Kaub

Monthly Mean Streamflow - Kaub

Monthly HQ1 Streamflow - Kaub
Monthly Low Flow (NM7Q) - September

Sea Surface Temperature
Kaub NM7Q - September

Sea Level Pressure
Kaub NM7Q - September
Final predictors: precipitation, temperature, soil moisture, SST, SLP, Z700 and U700

- Observed - Kaub NM7Q September
- Predicted - Kaub NM7Q September

Uncertainty bounds

\[ r = 0.91 \]
NM7Q Kaub - November

- Observed - Kaub NM7Q November
- Predicted - Kaub NM7Q November

r = 0.91

Streamflow [m$^3$/s]

Time [years]

[Graph showing observed and predicted streamflow with uncertainty bounds and a correlation coefficient of r = 0.91]
Monthly Low Flow (NM7Q) - July

Final predictors: precipitation, temperature, soil moisture, SST, SLP, Z700 and U700

$\text{r} = 0.97$
Monthly water levels – Kaub October

Final predictors: precipitation, temperature, SST, SLP, zonal wind, meridional wind
Seasonal forecast MQ – Kaub

- Observed - Kaub MQ DJF
- Predicted - Kaub MQ DJF
- Uncertainty bounds

- Observed - Kaub MQ MAM
- Predicted - Kaub MQ MAM
- Uncertainty bounds

- Observed - Kaub MQ JJA
- Predicted - Kaub MQ JJA
- Uncertainty bounds

- Observed - Kaub MQ SON
- Predicted - Kaub MQ SON
- Uncertainty bounds

Correlation coefficients:
- DJF: $r = 0.87$
- MAM: $r = 0.94$
- JJA: $r = 0.93$
- SON: $r = 0.86$
# Model evaluation

## NM7Q

<table>
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<tr>
<th></th>
<th>January</th>
<th>February</th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>October</th>
<th>November</th>
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<td>62</td>
<td>63</td>
<td>55</td>
<td>61</td>
<td>40</td>
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## MQ

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## Seasonal

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<th>JJA</th>
<th>SON</th>
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<tr>
<td>Miss %</td>
<td>15</td>
<td>16</td>
<td>7</td>
<td>10</td>
</tr>
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</table>
Transferability of the method – Elbe River

Final predictors: precipitation, temperature, SST, SLP, zonal wind, meridional wind

Source: Andy Philipp

July 2015
Advantages of this methodology

- It is inexpensive in terms of computationally and human resources.

- It does not require the use of a hydrological model, which is mostly not freely available and has high computational costs.

- It does not require the access to operational ensemble forecast data, like most of the available flood prediction products.

- It deals, at least partially, with the issues of stationary/non-stationary relationship between two variables.
Perspectives

Apply the same methodology to:

- Drought indices (e.g. Standardize Precipitation Index, Standardized Streamflow Index)
- Seasonal/annual minimum
- Smaller catchments

Possible improvements:

- Use observed/measured soil moisture
- Include snow cover (when and where available) to improve the potential predictability of winter and spring months

BfG is developing monthly to seasonal forecast products for the German waterways based on this statistical approach as well as hydrological and climatological model-based methods investigated in-house.
Thank you!

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