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Towards a pan-European assessment of low flow indices

CLAIRE LANG DELUS[1], GREGOR LAAHA[2], DANIEL KOFFLER[2], KERSTIN STAHL[3], HEGE HISDAL[4], CHRISTEL PRUDHOMME[5], MIRIAM FENDEKOVA[6] & WOJCIECH JAKUBOWSKI[7]

1 Department of Geography, University of Lorraine, France
claire.delus@univ-lorraine.fr

2 University of Natural Resources and Life Sciences, BOKU Vienna, Peter Jordan-Straße 82, A-1190 Vienna, Austria

3 University of Freiburg, Chair of Hydrology, Fahnenbergplatz, D-79098 Freiburg, Germany

4 Norwegian Water Resources and Energy Directorate, Oslo, Norway

5 Centre for Ecology and Hydrology, Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB, UK

6 Department of Hydrogeology, Comenius University, Bratislava, Slovakia

7 Department of Mathematics, Wrocław University of Environmental and Life Sciences, Poland

Abstract Water resources are increasingly limited and need to be protected in terms of both quantity and quality. In Europe, the Water Framework Directive sets a legal framework to make water resources management and environmental protection more effective. However, the Directive is not very explicit as to how low flows should be assessed and controlled and the choice of low flow indices remains the responsibility of each country. A working group on "Low flow indices" was launched within the EURO FRIEND-Water Low Flow and Drought Group to collect information on low flow practices in Europe and to achieve pan-European low flow mapping. In this paper we show both the process of the ongoing work and the way forward, and we present first results of the analysis. The paper illustrates how valuable the FRIEND network is to facilitate international cooperation, exchange of knowledge and data sharing.

Key words low flow indices; survey; European Water Archive (EWA); climate variability adjustment; streamflow–streamflow model; pan-European map

INTRODUCTION

The EU-Water Framework Directive (Council of the European Communities 2000) was introduced in 2000 to improve water resources management and environmental protection. The Directive sets quantitative and qualitative objectives for which the assessment of the state of water bodies under dry conditions constitutes a basic requirement, and the low flow indices are key variables. However, the Directive is not very explicit about how low flows should be assessed and controlled, and the choice of low flow indices remains under the responsibility of each country. In consequence, a broad range of low flow indices are used across Europe and practices regarding low flow monitoring or rules regulating water uses or ecological flows are wide ranging. A working group on "Low flow indices" has been launched within the EURO FRIEND-Water Low Flow and Drought Group to assess low flow indices across Europe. One aim of the working group is to review the most common low flow indices used in European countries and to provide pan-European low flow maps.

In this paper we focus on two major steps: (i) the compilation of an inventory of low flow practices especially regarding the use of low flow indices and regarding low flow monitoring, and (ii) a consistent dataset for future low flow mapping. We show both the process of the ongoing work and the way forward, and we present the first results of the analysis. The paper shows how valuable the FRIEND initiative is to facilitate exchange of knowledge and data sharing: The realization of a catalogue of low flow practices is based on a survey across Europe facilitated through the FRIEND network, and the pan-European low flow mapping will be based on the dataset of the European Water Archive, an initiative of the EURO FRIEND project.

SURVEY ON LOW FLOW PRACTICES IN EUROPE

To establish the inventory of low flow practices, a survey based on a questionnaire was carried out in 27 European countries. The aim of this survey is to compile a report that will give a wide as possible overview of low flow practices in European countries, namely on low flow monitoring systems, low flow indices in water uses and minimum environmental flow requirements.

Key role of the UNESCO-EURO FRIEND-Water network

The questionnaire was distributed in 27 countries. 16 countries promised their participation, and so far we have collected 12 completed questionnaires. Of the 12, 10 have been gathered with the help of members of the EURO FRIEND-Water Low Flow and Drought Group. Indeed, members of the FRIEND group have either filled in the questionnaire themselves, or forwarded it to experts in national water management. The FRIEND network played a key role in finding relevant contacts for several other countries. This work shows how efficient and valuable the FRIEND cooperation is for international water initiatives. The survey is still ongoing and the FRIEND network may be helpful in collecting questionnaires from remaining countries.

Preliminary results of the survey

A first summary based on countries that have already responded can be made (see Tables 1 and 2):

Low flow monitoring One aim of the questionnaire is to survey practices regarding "real-time" low flow monitoring, which is also directly linked to drought monitoring. It appears that for the majority of the countries that responded, monitoring is not specifically done for low flows but continuously for the whole flow range, encompassing in most cases low flows or drought situations.

Thereby in the Czech Republic, river basin authorities and the Czech Hydrometeorological Institute provide actual river discharges monitoring which is displayed online and indicates whether a river is in "drought", "mean stage", "flood watch", or a particular state. In addition, in the UK hydrological monitoring encompasses the whole regime. On a national scale, the Centre for Ecology and Hydrology conducts the "National Hydrological Monitoring Programme" (NHMP). Monitoring is also done at regional scales by Environmental Agencies, which produce monthly and weekly "Regional Water Situation Reports". In Finland, the Finnish Environment Institute has a real time hydrological model that shows online actual river discharges for the whole area of Finland. This "Watershed Simulation and Forecast System" does not automatically give warnings on possible low water levels, but this could be easily done as it gives warning on possible flood events. In Germany there is no specific low flow monitoring system, except in Bavaria. However, some of the flood forecasting centres may indicate low flow on their online real-time flow maps. In Bavaria, three categories assess the current low flow situation: "low",

Table 1 Hydrological monitoring and specific plans for low flow and drought.

Country	Hydrological monitoring systems and web link
Czech Republic	Hydrological monitoring which encompasses drought assessment: hydro.chmi.cz; voda.gov.cz
Finland	Hydrological monitoring: http://www.ymparisto.fi/default.asp?node=27174&lan=en
France	National drought plan: http://propluvia.developpement-durable.gouv.fr
Germany	Low flow monitoring system only in Bavaria: http://www.nid.bayern.de
	Flood monitoring centres may indicate low flows on their maps: www.hochwasserzentralen.de
Norway	Hydrological monitoring which encompasses drought assessment: http://www.nve.no/en/Water/Data-databaser/Real-time-hydrological-data
Poland	Operational System for Providing Drought Prediction and Characteristics: http://posucha.imgw.pl/
Slovakia	No monitoring for low flows but drought is evaluated and drought maps are displayed online within hydrological yearbooks. Example: http://www.shmu.sk/File/kvantPV2011/map8_3_md2011.pdf
The Netherlands	No specific system but for main rivers current streamflows are compared to defined minimum flows
United Kingdom	UK-wide monitoring conducted by the National Hydrological Monitoring Programme (NHMP): http://www.ceh.ac.uk/data/nrfa/nhmp/nhmp.html
	Regional monitoring from Environmental Agencies: http://www.environment-agency.gov.uk/research/library/publications/33995.aspx

"very low" and "lowest". In Norway, the Norwegian Water Resources and Energy Directorate displays real-time river discharges online and indicates with specific red colours whether a river is in drought based on a specific drought classification. In France there is a specific national plan for low flows and drought, based on four warning levels, namely "vigilance", "alert", "reinforced alert" and "crisis". Each warning level leads to specific water restrictions. Low flow indices used to set the different levels are locally decided by framework decrees and hence may vary between basins. In Poland, the Institute of Meteorology and Water Management National Research Institute provides forecasts and warnings on hazardous hydro-meteorological situations. A device called "Operational System for Providing Drought Prediction and Characteristics" was developed recently, specifically for drought monitoring.

In Slovakia, a real time hydrological forecast model shows online actual river discharges for 192 gauging profiles around the whole country. This system does not give warnings on possible low water levels, but this could be easily done as it gives warning on possible flood events. However, the Slovak Hydrometeorological Institute provides hydrological yearbooks describing the low flow situation in the 12 main river basins. In the Netherlands, there is no publicly accessible low flow monitoring. However, for the main rivers, measured streamflows are compared to defined minimum flows, which are of major concern for dike stability. If the current flow is lower than the minimum flow, a committee will meet to discuss the situation. In other countries, e.g. Belgium, local water managers do low flow assessment by comparing current flows with low flow indices or historical events.

However, one point regarding the sample of surveyed countries has to be noted as it could explain why in most cases there is no specific system for low flow monitoring. Indeed, water scarcity is not a major issue in several of the countries that responded, whereas several questionnaires for southern European countries are still missing. Furthermore, specific low flow or drought monitoring systems are under development in some countries: the UK is currently

Table 2 Low flow indices operationally used in European countries.

	$Q_{n,T}$	Q_x	MAM_n	Index based on monthly flows	Other index
Belgium		Q_{95}, *Q_{335}*	MAM_7		
Czech Republic		***Q_{355}***, **$Q_{330 \& 364}$**	MAM_7	**Monthly minimum flow**	
Finland		**Q_{95}**	MAM_1		
France	**$Q_{m,5}$** **$Q_{3,20}$**	Q_{335}	**MAM_3** *MAM_n*	Monthly minimum flow	**10 or 20% of mean annual flow**
Germany		*Q_{75} (of month)*	$MAM_{1,7,30}$		**$^1/_3$ of MAM_1**
Bavaria			*MAM_1*		*Lowest daily streamflow*
Italy	$Q_{7,2}$				
Norway		*$Q_{90 \& 75}$*, Q_{95}, **Q_{96}**			
Poland			**MAM_1**		Standardized Runoff Index
Slovakia	$Q_{7,100}$	*Q_x*, **Q_{355}, Q_{364}**	MAM_7		
Slovenia		**Q_{95}**	MAM_{30}	**nQn**: Monthly minimum flow **sQn**: Average of nQn	
The Netherlands					
United Kingdom		**$Q_{95 \& 90}$**		*Monthly flows*	

Italic: low flow indices for monitoring; **Bold**: low flow indices used to regulate water uses and/or to define environmental flows; Normal: indices which may be used to describe low flow long-term average conditions. This is based on the survey and it may not be exhaustive reviewing the outputs of the NHMP and plans to extend it to drought monitoring, which may involve the use of low flow indices; in the Czech Republic, the TGM Water Research Institute is developing a system for managing emergency situations associated with drought and water scarcity; in Slovakia, the scientific research project entitled "Prognosis of hydrological drought occurrence in Slovakia" was recently approved.

Low-flow indices The survey aims in particular to summarize low flow indices used across Europe. Table 2 gives a first overview of the most widely used indices classified in five categories: (i) $Q_{n,T}$: annual n-day minima with a given return period T, (ii) Q_x: low flow quantile from the flow-duration curve, (iii) MAM_n: mean annual n-day minima, (iv) index based on monthly flows, and (v) other index. The table shows that the most commonly used indices are low flow quantiles and Mean Annual Minima of different n-durations. Table 2 also suggests that only a few countries use indices based on frequency analysis (France, Italy and Slovakia).

A detailed presentation of each index and its purposes for each country is not feasible here. Instead we focus on low flow indices used for "real-time" flow assessment to supplement the previous part on monitoring practices. The low flow indices frequently serve as a threshold for defining the low flow or drought state of the hydrograph. In Norway, for example, the drought classification is based on low flow quantiles: if the current value is below Q_{90} the river is classified in drought and if the value is between Q_{90} and Q_{75} it is classified as below normal, i.e. dry. In Bavaria (Germany), the low flow monitoring is based on the following classification: "lowest" if the current streamflow is equal to the lowest daily streamflow ever measured; "very low" if the current streamflow is below MAM_1; "low" if the current streamflow is below 75% of all values in a given calendar month and "not low" for the rest. In the Czech Republic, Q_{355} is used to define the drought situation. In Slovakia, lowest average daily discharges are represented in annual maps in terms of low flow quantiles formulated in days. In France, current flows are compared to four warning levels previously described. Values defining the various thresholds of the classification may vary locally but they are mostly based on annual n-day minima or monthly minima values of a given return period.

At the present state of the analysis we can summarize that low flow indices used to define thresholds in monitoring systems are wide ranging across Europe, but they may also vary within a country. Once the inventory of low flow indices and their uses is completed, relationships between indices will be explored by statistical analysis to identify groups of indices, to highlight their similarity and differences, and to assess their ability to characterize extreme conditions. The outcomes of the analysis will be synthesized through pan-European low flow maps.

PAN-EUROPEAN LOW FLOW MAPPING

The value of the European Water Archive (EWA) for pan-European assessments

The European Water Archive (http://www.bafg.de/GRDC/EN/04_spcldtbss/42_EWA/ewa.html) is a river discharge database of the UNESCO EURO FRIEND-Water group. This database, available through the GRDC (Global Runoff Data Centre), is the most comprehensive archive of long-term daily flow data at the European scale and hence will provide the core of the dataset for this pan-European low flow mapping. Currently the EWA contains daily data for more than 4000 stations in 30 countries. However the achievement of consistent maps of low flow characteristics requires recorded data for a long-term standard period while there is a very high diversity in average record length and covered period in the EWA database (Fig. 1). Data of 20 years duration or more is often recommended as a minimum record length (e.g., Tallaksen & van Lanen, 2004) while many EWA gauging stations have much shorter observation periods. However, stations with short records will be useful as the data can be correlated with a longer time series from nearby gauging stations, by means of climate adjustment methods (Laaha *et al.*, 2005; WMO, 2009).

It is therefore important to identify the optimal period which should be a balance between the highest number of nearly-complete stations over a 20-year period and the lowest number of stations without any data. From an initial assessment it was decided to select a "main sample" of

Fig. 1 Various lengths in time-series of gauging stations from the EWA database.

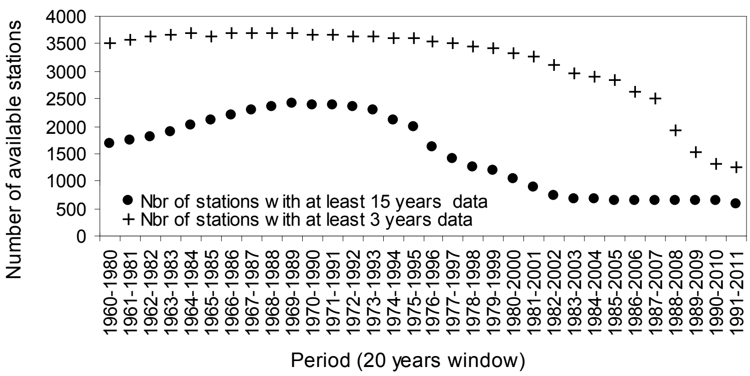

Fig. 2 Number of gauging stations available in the EWA database according two criteria.

nearly-complete stations over a 20-year period (with less than 5 years of missing data) and an "additional dataset" of stations with at least 3 years of data. The main sample will be used to calculate and map low flow characteristics, but also assist in climate adjustment to make low flow characteristics for additional stations with shorter record periods compatible with the 20-year standard period.

Figure 2 suggests that the 1960s and 1970s meet best the previous criteria while the number of stations nearly-complete over 20 years decreases strongly for recent periods. Consequently, the two successive standard periods 1966–1985 and 1986–2005 were selected for low flow mapping: the first period because of completeness, the second period to assess possible changes in the low flow conditions during the last decades. Figure 3 shows the corresponding datasets for these two periods. Whilst for the first period (1966–1985) the dataset seems consistent and well suited, the spatial coverage of nearly-complete stations (in black) looks insufficient for the recent period (1985–2005) and we discuss this issue in the Outlook. For now, the main task is to identify reliable methods to infer low flow characteristics for short record periods from longer record periods.

Low flow estimates for short streamflow records of additional stations

We compare two methods for inferring long-term low flow characteristics for a site with short records (subject site) from nearby stations: climate adjustment and streamflow–streamflow modelling. A dataset of 33 gauging stations located in the East of France with a common period of

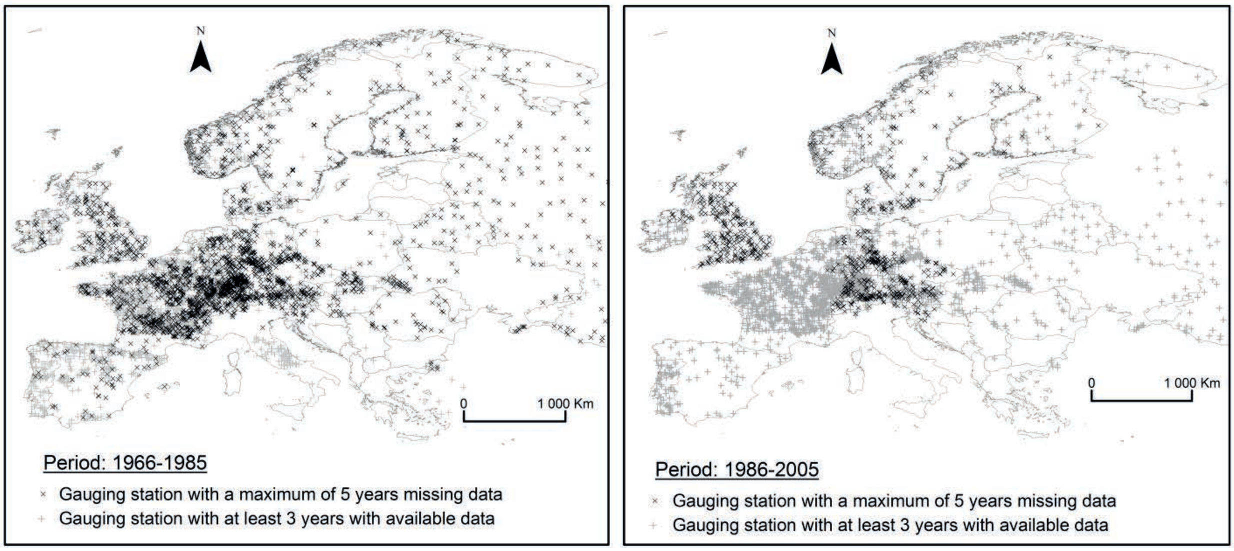

Fig. 3 Dataset selected from the EWA database for pan-European low flow mapping ("main sample" in black and "additional stations" in grey; left: 1966–1985 period, right: 1986–2005 period).

daily data (1990–2009) has been identified as suitable (one method required necessarily for each station a downstream station). The evaluation is based on the low flow characteristic Q_{95} calculated for the period 1990–2009 and for hypothetical shorter periods to assess the performance of various methods.

Climate adjustment consists of calculating the ratio between low flow characteristic from the whole period and from the shorter overlapping period between a donor (long record) and a site of interest (short record). Laaha *et al.* (2005) compared several donor selection methods for climate adjustment applications and showed that the "Downstream donor selection" (i.e. the next downstream station is chosen as donor) performs better than other methods based on proximity in Euclidean space, or similarity in terms of catchment characteristics. The streamflow–streamflow method is based on a streamflow–streamflow model (Andréassian *et al.*, 2012) applied between a site and a donor: The model is calibrated between the subject site and all potential donors over the common overlapping period. Among all potential donors we retain a single best donor in terms of efficiency based on the Nash-Sutcliffe criterion (here calculated on logarithmic values to focus more on low flows). Once the best donor is selected, two methods are compared to estimate the low flow characteristic Q_{95}: (i) climate correction as presented above ("QQ donor selection"), and (ii) streamflow–streamflow modelling to simulate daily streamflows at the subject site for the missing period; the low flow characteristic Q_{95} is then predicted from the simulated hydrograph ("QQ simulations").

The various methods are compared for different lengths of overlapping periods, following the same methodology as presented in Laaha *et al.* (2005). The performance of the methods is assessed with the root mean square error, RMSE, calculated between adjusted low flow characteristics from hypothetical short records and low flow characteristics calculated for the whole standard period. Figure 4 shows that both methods perform well, with a slight advantage of the downstream donor selection method for total discharges (left panel). For specific low flows, the downstream donor selection performs slightly better for a period longer than 10 years while the streamflow–streamflow model performs best for records shorter than 10 years.

Low flow characteristics for stations with short record periods may hence be estimated based on "QQ simulations" if the available period is shorter than 10 years and on "Downstream donor selection" if longer than 10 years. However, stations within the EWA dataset do not consistently have a downstream donor and in this case QQ simulations may give an alternative.

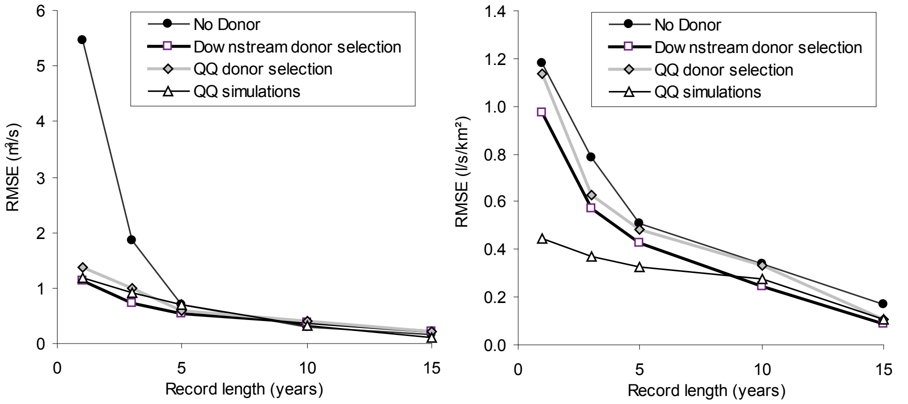

Fig. 4 Absolute errors RMSE of Q95 (left: m^3/s; right: $l/s/km^2$) estimated for shorter records than 20 years compared to 20 years records ("No donor" means that Q95 was directly calculated from hypothetical short records).

OUTLOOK

This is an ongoing work and the priority is to finish the survey and the catalogue of the most prominent low flow indices. These indices will be compared, synthesized and grouped through pan-European low flow maps which will be carried out for two periods: 1966–1985 and 1986–2005.

Additional dataset from FRIEND partners The EWA database will provide the core of the dataset. However, the database is not updated for recent periods and this issue is currently under consideration within the EURO FRIEND-Water Low Flow and Drought Group. We intend to ask FRIEND partners to provide low flow characteristics rather than streamflow data. The calculation of low flow characteristics will be facilitated by a common software tool, lfstat (Koffler & Laaha, 2013).

Low flow estimates for short records The downstream method and the streamflow–streamflow model show promising results, but predictions may be improved by using multiple neighbours instead of a single neighbour.

Low flow mapping and climate change The final step will be the compilation of a European low flow atlas, which would be a rich source of hydrological information on minimum flows across Europe. Low flow mapping will be based on two successive standard periods and changes in low flow characteristics will be explored and if possible related to climate change or to local factors.

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REFERENCES

Andréassian, V., Lerat, J., Le Moine, N. & Perrin, C. (2012) Neighbors: Nature's own hydrological models. *J. Hydrol.*, 414–415, 49–58.

Koffler, D. & Laaha, G. (2013) LFSTAT – Low-Flow Analysis in R. EGU General Assembly. *Geophys. Res. Abstracts* Vol. 15.

Laaha, G. & Blöschl, G. (2005) Low flow estimates from short streamflow records—a comparison of methods. *J. Hydrol.* 306(1/4), 264–286.

Tallaksen, L. M. & van Lanen, H. A. J. (eds) (2004) *Hydrological Drought. Processes and Estimation Methods for Streamflow and Goundwater*. Developments in Water Science, 48, Elsevier Science BV, The Netherlands.

WMO (ed. by S. Demuth & A. Gustard) (2009) Manual on low-flow estimation and prediction, Operational Hydrology Report No. 50, WMO-N°1029, Geneva, Switzerland.