Regional assessment of low flow processes and prediction methods across European regimes

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Abstract In this contribution we present two pilot studies initiated from the EURO FRIEND-Water Low Flow group. The first study gives an example for bi-lateral assessment of regionalization methods for predicting low flows at ungauged sites. The study covers the Meuse and Moselle basin in NE-France and investigates the performances of the geostatistical method top-kriging and a process-based method, the catchment model GR4j, in different hydrological environments. The second study aims to explore low flow generating processes on a catchment scale by comparing runoff signatures on a regional scale. Based on hydrological drought types we use hot spots of close-by gauges to explore climate–catchment interactions based on catchment similarity. The outcome shall build the foundation for a hydrological drought typology across European regimes. The examples illustrate that FRIEND-Water provides a very precious network which facilitates international collaboration of water experts to tackle wicked water problems.

Key words low flows; droughts; regionalisation; top-kriging; drought typology

INTRODUCTION

Learning from similarity and differences of runoff regimes, to enhance our understanding of drought-generating processes and to develop more accurate regionalisation methods for predicting low flows at ungauged sites, has always been a very active research field of the EURO FRIEND-Water Low Flow and Drought Group. Major achievements include the development of regionalisation models and atlas products for several countries (Austria, Norway, SW-Germany, Switzerland, and the UK), but such models are still missing for other countries. Therefore, it is important to share and transfer the findings to other regions to fill in the picture on the spatial dimension of low flow and drought hazard across Europe.

One aim of the working group on regional assessment within the EURO FRIEND Low Flow and Drought Group is to continue the work carried out for the PUB Synthesis Report (Blöschl *et al.*, 2013) on low flow estimation (Laaha *et al.*, 2013b), and to focus on identified research gaps. While the PUB Synthesis Report assesses the performances of regionalization methods from a meta-analysis of existing studies, we will focus on bi- to multilateral studies. This allows us to address questions about the functioning of selected models under specific hydrological conditions in more detail, which can then be applied to model improvements. A second aim is to extend the assessments of the PUB report towards a more detailed analysis of drought types and catchment functioning, to shed light on the role of climate catchment interactions in drought generation.

Two pilot studies were initiated from the EURO FRIEND-Water Low Flow Group which contribute to these aims. The first study, on low flow regionalisation in the Meuse and Moselle basin, gives an example for bi-lateral assessment of regionalization methods for predicting low flows at ungauged sites. The second study, on climate-catchment interactions for low flows in Austria, aims to explore the link between low flow vulnerability and hydrological drought types (Van Loon & Van Lanen, 2012) to shed light on low flow generating processes. In this paper we show both the process of the ongoing work and the way forward, and we present results of the analysis.

STUDY 1: ASSESSMENT OF REGIONALIZATION METHODS

Regionalisation of low flows is currently dominated by statistical methods. The PUB-Report summarized the state-of-the-art of low flow regionalisation and pointed out that process-based methods are under-represented in the literature, so a more detailed analysis of these would be of interest (Laaha *et al*., 2013b, Salinas *et al*., 2013). In this study we aim to test a process-based method, i.e. catchment modelling, through detailed assessment of its predictive performance depending on topological, geological and climatic conditions. We further aim to test the geostatistical method top-kriging (Laaha *et al*., 2013a) which performed notably well in the Austrian study area in a different environment, and to learn from the relative skills of both methods to enhance regionalization. This is achieved in a bi-lateral study, using the concept of model and data sharing.

Catchment modelling is based on the GR4j model (Perrin *et al*., 2003), a parsimonious daily four-parameter rainfall–runoff model. Its major components are a production store and a nonlinear routing store. Parameters still need to be calibrated with gauged streamflow records, so some regionalisation method is needed to apply the method for ungauged sites. In this study, the model is regionalised by model output averaging (Oudin *et al*., 2008; AERM-UL Report, 2012), which was shown in a preliminary analysis to clearly outperform regional or regression and parameter averaging procedures for the study area. The method takes the model outputs (i.e. hydrographs) of the four nearest gauges (in terms of Euclidean distance in geographic space), and calculates the estimate for the subject site as an equally weighted average of these outputs. From this predicted hydrograph, the low flow characteristic Q95 of the subject site is calculated.

Top-kriging is a geostatistical method that accounts for the river network hierarchy (Laaha *et al*., 2013b). Low flow characteristics Q95 of an ungauged site are predicted by a weighted average of the Q95 values of the gauges as in standard kriging methods, but in top-kriging the weights are estimated by a family of variogram models (regularisations) for different catchment areas (kriging support), which accounts for the different scales and the nested nature of the catchments. This assures that kriging weights are distributed to both hydrologically connected and unconnected sites of the stream network according to the data situation: top-kriging gives most weight to close-by sites at the same river system, but when the next hydrologically connected site is far away, more weight is given to a close-by site at an adjacent, unconnected river system. The distribution of weights is in contrast to ordinary kriging and stream distance-based kriging which do not account for both spatial proximity and network connectivity.

The methods were tested on an extensive dataset of the Meuse and Moselle basin and a few catchments of the Rhine basin to cover the whole Vosges mountain area (area approx. 31 000 km^2), consisting of 103 gauging stations with only minor anthropogenic influences (density: 3.3 stations / 1000 km^2). The study area is subject to maritime temperate climate, with considerable variability of precipitation (ranging from less than 800 mm for lowland to more than 2000 mm for mountainous areas) and evapotranspiration (ranging from 550 mm to more than 650 mm). Geology varies as well, and the main formations are limestone, marl and clay in lowlands, and sandstone, schist and granite in the mountains. These physiographical differences give rise to different aquifer capacities and a high spatial variability in low flows.

Figure 1 presents scatterplots of predicted and observed values of both regionalisation methods. Overall, both methods perform well. Top-kriging exhibits a coefficient of determination of $R_{CV}^2 = 0.61$ that is somewhat lower than in other studies reported in the PUB report. This may be attributed to the large spatial variability in geology and strong precipitation gradients. The performance of the process-based method is somewhat lower than top-kriging ($R_{CV}^2 = 0.50$), but significantly higher than other studies on process based models reported in the PUB report.

To shed light on the reasons for the different performances, we stratified the results according to stream topology and physiographic factors. The analysis yielded that both methods perform better for non-headwater (NHW) catchments with an upstream gauge than headwater catchments (HW). The respective performances for NHW and HW are $R_{CV}^2 = 0.75$ and 0.51 for top-kriging, and $R_{CV}^2 = 0.59$ and 0.45 for the rainfall–runoff model. For top-kriging, the results are in line with the finding of Laaha *et al.* (2013a) that in headwaters top-kriging tends to extrapolate the values of the downstream gauge, unless close-by donors in neighbouring headwater catchments are available. This extrapolation might yield some bias due to precipitation gradients and different storage

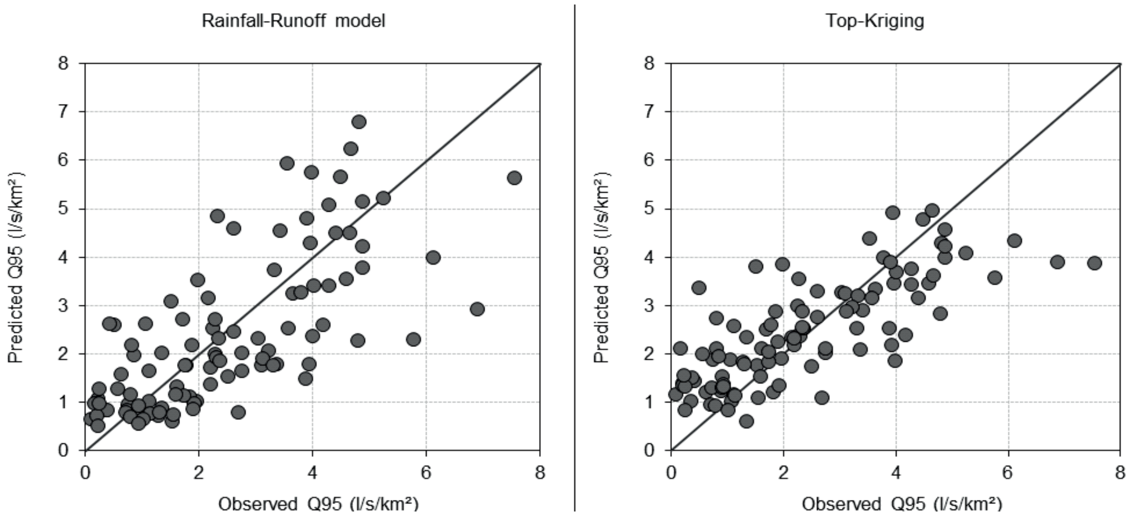

Fig. 1 Scatterplots of predicted (cross-validation) and observed values of specific low flows Q95 (in $l\ s^{-1}\ km^{-2}$) for two regionalisation methods, rainfall–runoff model (left) and top-kriging (right).

properties of the headwaters compared to the more downstream areas. The effect on the rainfall–runoff predictions is similar for headwater catchments with high specific low flows. This is likely due to a bias in rainfall estimates in this mountainous area. Indeed, the model inputs are based on the SAFRAN distributed data validated throughout the French territory (Quintana-Seguí *et al.*, 2008) which shows a fairly strong bias in this area (Vidal *et al.*, 2010).

From all results, we conclude that top-kriging performs better than the process-based method as we expected, but the results for the rainfall–runoff model used in this study seem very encouraging. We believe that one reason for the good performance of the process-based method is its parsimonious structure which makes it much more suitable for regionalisation than other less parsimonious models. We have also seen that the regionalisation method used to apply the process-based method at ungauged sites had a major impact on the performance. The model-output averaging method performed much better than parameter-averaging methods, but still has potential for improvement. First, we selected the donor gauges by a rather simple criterion from distance in geographic space, and a more elaborate criterion will likely improve the estimates. Secondly, the output averaging was performed by an unweighted average of the model outputs of the donor sites, and it needs to be proved if and how weights can be determined to better represent the degree of similarity between hydrographs during low flows, and to better consider untypical catchments like karstic basins. Furthermore, the model was not specifically tailored for low flows and a modification of the model structure in the groundwater component may improve low flow predictions in permeable basins of the studied area, as shown in Lang *et al.* (2008). However, this modified version of the model is less parsimonious and may be less suitable for regionalisation. Finally, a correction of the rainfall bias for the mountainous area is anticipated to improve predictions of headwater catchments located in the Vosges mountains, which were of major concern for the practical application of the model. We also aim to develop a combined method which integrates the advantageous properties of the geostatistical method and the process-based method to estimate the low flow part of the hydrograph at ungauged sites more accurately than existing state-of-the-art methods.

STUDY 2: LOW FLOW TYPOLOGY – CLIMATE AND CATCHMENT INTERACTIONS

The second study builds on the work of Van Loon & Van Lanen (2012) and Van Loon (2013) who established a drought typology based on a classification of meteorological events. They distinguished six hydrological drought types, i.e. (i) classical rainfall deficit drought, (ii) rain-to-snow-season drought, (iii) wet-to-dry-season drought, (iv) cold snow season drought, (v) warm snow season drought, and (vi) composite drought. The processes underlying these drought types are the result of the interplay of temperature and precipitation at catchment scale in different seasons. They also found differences in the drought characteristics between fast and slow responding catchments and between hydrological drought types, but this catchment-specific component was not fully explored.

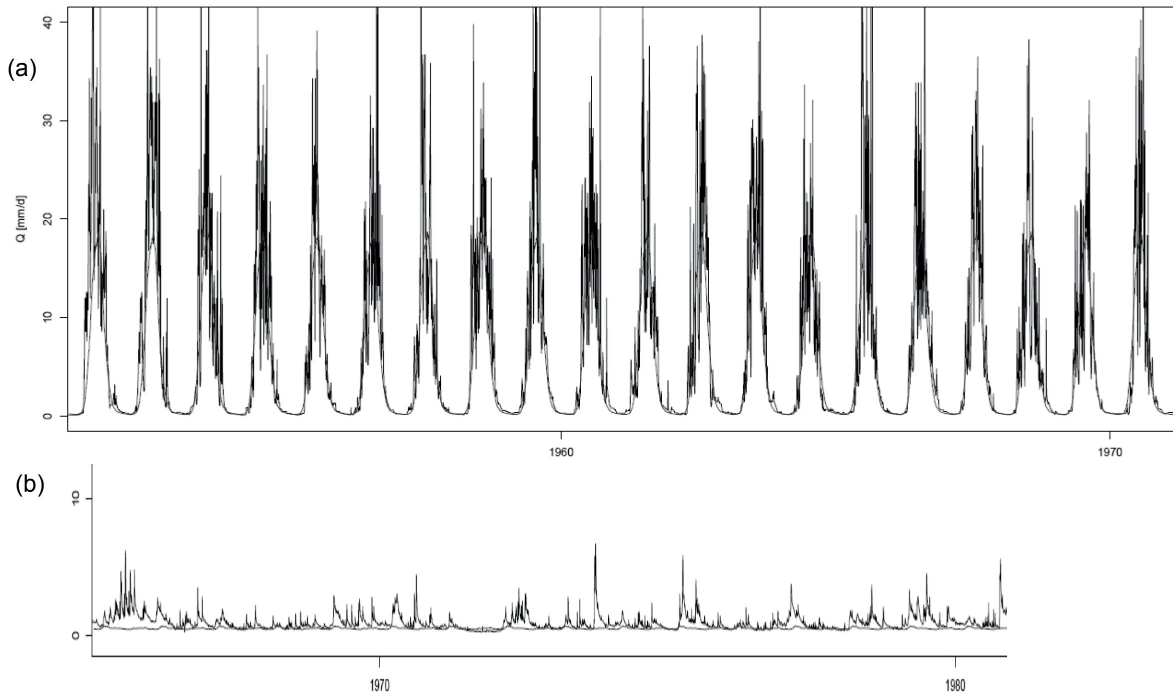

Fig. 2 Example of time series of discharge (higher peaks) and threshold level (lower line) for exemplary catchments of two contrasting hot spots; (a) Hoalp (high Alps; upper panel), (b) Gurk (lower Alps, lower panel).

In this study, we use an Austrian dataset of discharge measurements at 42 gauges in contrasting areas to study the effects of climate and catchment characteristics on streamflow drought characteristics in a systematic way. As this is a first explorative analysis, we aim to find areas for further research. To separate the effects of climate and catchment characteristics, we use a selection of hot spots of close-by gauges, similar to those of Gaal *et al.* (2012) for floods, which are homogeneous in terms of climate: Waldviertel (Waldv), Weinviertel (Weinv), Bregenzer Wald (Brewa), Gurktal (Gurk), Hochalpen (Hoalp) and Oetztal (Otzt). The hot spots also represent different geological conditions, but in this respect they are not necessarily homogeneous. Drought events (i.e. seasonal streamflow anomalies) are identified with the widely-used threshold level approach and we used a variable threshold based on the 80th percentile of the daily flow duration curves of a 30-day moving window. Drought characteristics that were analysed are duration and standardized deficit (deficit volume divided by the long-term mean of the variable), further called deficit for brevity, that we plotted in duration–deficit plots (as in Van Lanen *et al*., 2013; Van Loon *et al*., 2013). To quantify the orientation of the cloud of points in these plots, we fitted a linear regression line through the drought events. The slope of the regression line and the coefficient of determination (R^2) of the fit were used to compare hot spots. The smaller the slope, the smaller the increase of deficit with duration.

In a first analysis we looked at the variability of flow regimes across the study area. The time series of daily discharge and threshold level (Fig. 2) show clear differences between the hot spots, as was also noted previously in Laaha & Blöschl (2006) and Gaal *et al.* (2012). The role of seasonality in climate (which is mainly temperature-driven in the study area) is very clear in the Alpine hot spots, such as Otzt and Hoalp (Fig. 2(a)), resulting in a clear seasonality in the threshold level. Other hot spots like Waldv and Gurk (Fig. 2(b)) have higher baseflow and the hydrograph is more represented by rainfall peaks in any season. This leads to a quite flat threshold level in those hot spots.

In a second analysis we focused on the relationship of drought duration and deficit. The duration-deficit plots of the drought events mostly had the expected linear shape (Van Loon *et al*., 2013), e.g. that of Weinv (Fig. 3(a)), where deficit volumes are linearly related to duration. However, some hot spots had a duration-deficit plot with a divergent pattern in which long duration droughts can either have low or high deficit, e.g. that of Brewa (Fig. 3(b)). This is related to the strong seasonality in Alpine catchments, where the threshold level is high in summer and droughts can develop freely and low in winter and drought deficit is limited by zero. A similar effect was found in soil moisture droughts in semi-arid seasonal climates by Van Loon *et al*. (2013), albeit with contrasting seasonality.

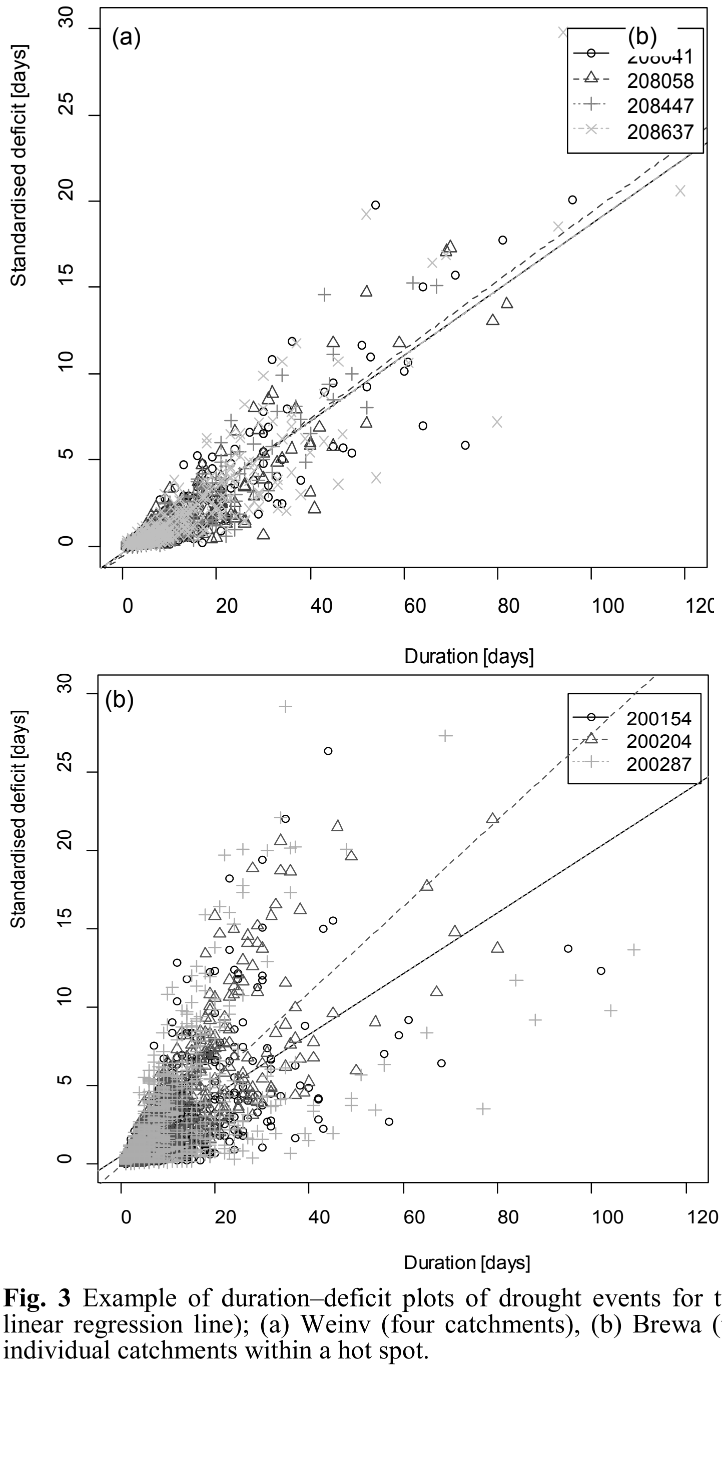

Fig. 3 Example of duration–deficit plots of drought events for two contrasting hot spots (including linear regression line); (a) Weinv (four catchments), (b) Brewa (three catchments). Symbols refer to individual catchments within a hot spot.

Finally, we screened whether the duration-deficit relationships depended on climate and catchment factors. Van Lanen *et al.* (2013) found that the strength of the relationship mainly depended on climate type (Köppen-Geiger classification) and on groundwater storage. We wanted to assess if we could find similar effects in the Austrian study area, where Alpine catchments belong to cold climate (Type D) and the lower situated catchments belong to warm temperate climate (Type C). The analysis yielded a strong negative relationship with elevation (the spread increased with altitude) which is likely an effect of climate. The effect might be due to the seasonal threshold levels, but also due to the fact that summer and winter droughts are generated by different processes with differing recession behaviour. Besides the effect of elevation, we found a strong positive relationship between the density of the stream network and the slope of the regression line. The important effect of the stream density in these hot spots and the interrelationship between stream density and other geological and climate parameters on different time scales were previously discussed in Gaal *et al.* (2012). This is an issue that will further be explored in a more detailed analysis of within- and between-hot spot variability.

SUMMARY AND CONCLUSIONS

We presented two ongoing pilot studies initiated from the EURO FRIEND-Water Low Flow group. The first study gave an example of bi-lateral assessment of regionalization methods for predicting low flows at ungauged sites aiming to develop improved predictive models. The second study combined different expertise in drought and low flow analysis to foster process understanding. The examples illustrated that FRIEND-Water provides a very precious network which facilitates international collaboration of water experts to tackle wicked water problems.

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