Synthesizing changes in low flows from observations and models across scales

KERSTIN STAHL[1], JEAN-PHILIPPE VIDAL[2], JAMIE HANNAFORD[3], CHRISTEL PRUDHOMME[3], GREGOR LAAHA[4] & LENA M. TALLAKSEN[5]

1 University of Freiburg, Chair of Hydrology, Fahnenbergplatz, D-79098 Freiburg, Germany
kerstin.stahl@hydrology.uni-freiburg.de

2 Irstea, UR HHLY, 5 rue de la Doua, CS70077, F-69626 Villeurbanne Cedex, France

3 Centre for Ecology and Hydrology, Benson Lane, Crowmarsh Gifford, Wallingford OX10 8BB, UK

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

5 Dept. of Geosciences, University of Oslo, PO Box 1047 Blindern, N-0316 Oslo, Norway

Abstract This contribution presents a comparison of the observed and projected low flow trends and changes for the European domain (as derived from homogenized large-scale datasets and model applications) with the mosaic of results obtained from pan-European and national-scale studies. The large-scale datasets include the streamflow records held in the European Water Archive and the WATCH large-scale model ensemble. National studies are available from Norway, the UK, southern Germany, Austria and France. The comparison shows that large-scale model experiments focus mostly on the general pattern of seasonal flow changes, whereas national to regional scale studies tend to focus on absolute low flow values and deficits below relevant thresholds and often stratify their assessments by hydrological regime or dominant process control. The study concludes that different levels of information can indeed benefit synthesis assessments of low flow changes at the hydrological planning scale.

Key words low flow; Europe; climate change, trend analysis, scenarios

INTRODUCTION

Low flows create a number of challenges for aquatic ecology and a variety of human water uses. They can affect drinking water supply either directly or indirectly through reduced bank infiltration into groundwater, energy production, waterborne transportation, industrial use, etc. In times of global warming and expected increase in the occurrence and severity of hydrological extremes, there is considerable concern over potential changes in low flows. In Europe an exacerbation of low flows would also make it more difficult for countries to meet their obligation to improve the ecological status of water bodies according to the EU Water Framework Directive.

The assessment of changes in low flows as a response to climatic change, however, presents a number of challenges. Common methods include statistical trend analyses applied to observed streamflow time series or model experiments for the recent past, and model chain experiments – from Global Climate Models (GCMs), to Regional Climate Models (RCMs), to hydrological models – for future scenarios. All approaches have their strengths and weaknesses and the use of a diversity of observational datasets, methods and models, across a range of temporal and spatial scales, further complicate comparative assessments.

A key aim of the working group on climate change impacts within the Euro FRIEND-Water Low Flow and Drought Group is to harmonize and synthesize different assessments for the European domain. This contribution first systematically reviews methodologies applied for assessing changes in low flows and streamflow droughts in Europe, discussing their strengths and weaknesses. It then presents a comparison of the observed and projected low flow trends and changes, as derived from homogenized large-scale datasets and model applications, against the mosaic of results obtained from national scale studies. The latter is based on selected case study countries from active members in the Euro FRIEND-Water Low Flow and Drought Group, i.e. Norway, the UK, France, Germany, and Austria.

DATASETS AND METHODOLOGIES

Low flow indices and change metrics from observations

Assessments based on changes in observations differ in the data (catchment) selection criteria and the low flow index under study. Whereas all data have undergone quality control, some studies are based on hydrological reference networks with selection criteria such as near-natural flow, but others are vague or unspecific about this aspect. Studies also differ in the time period covered, in the method and metric they use to calculate and express change over time, and in the statistical tests they apply (if any). Large-scale European datasets of observed streamflow from the European Water Archive (EWA) initially focused on the "best coverage" period from 1962 to 2004. However, realizing the sensitivity to the period under study, Hannaford *et al*. (2013) explored the influence of start and end date on the derived trends in more detail.

Table 1 gives an overview of annual low flow and drought indices used in selected multi-national and national trend studies in Europe. Daily streamflow data are often aggregated to indices of somewhat longer spells for specific seasons. One is the annual average 7-day minimum flow (AM(7)), which has been used in the UK, Germany and also for the summer season in pan-European studies based on the European Water Archive (EWA) data (a unique European database of daily streamflow series established by the Euro FRIEND-Water programme: http://ne-friend.bafg.de/servlet/is/7413/). Changes in the annual Q95, the flow that is exceeded 95% of the time, also referred to as a percentile of the flow duration curve, have been assessed in Austria and in the UK for different seasons. The annual monthly minimum flow with a 5-year return period (QMNA5) is a legal threshold in France and is therefore commonly used in national studies for assessing changes in low flows. Several studies have also used threshold level based streamflow drought indices, such as deficit volume, duration, and severity. Different thresholds have been used, such as the Q85 in France and the Q70 in the Nordic countries, and the mean annual minimum flow in Germany. Furthermore, some recent studies have used indices that adapted the concept of the standardized precipitation index, a climatic drought index, to streamflow. Examples include a national-scale drought reanalysis study in France that developed a Standardized Flow Index (Soubeyroux *et al.*, 2010) and European and UK studies that used a regional deficiency index (Hannaford *et al.*, 2011) based on threshold-based streamflow drought definition. A multitude of sub-national and basin-scale studies which were not considered here have used an even larger diversity of indices.

Measures of trend magnitude for the annual low flow indices described above include mainly the slope of a linear regression with time (year) or the Sen-slope. Units vary from mm/year, decade or period to percentage of the mean or standard deviations over various time intervals. Most national or regional studies carry out statistical tests either on the slope of the regression or (more often) the Mann Kendall (MK) test, sometimes after pre-whitening or block bootstrap methods (to account for autocorrelation in the series) and sometimes under consideration of spatial correlation. A few studies have carried out tests for field significance.

Modelling experiments projecting the future

Future changes are generally derived with model chain experiments in which GCM or RCM output is downscaled and/or bias-corrected to provide input to hydrological models. Most studies use climate model output from one of the earlier Coupled Modelled Intercomparison Projects (CMIP) or the ENSEMBLES project, mostly under the SRES A1B or A2 emissions scenarios. The downscaling and bias-correction are usually done specifically for the respective study. Likewise, the variety of hydrological models used is large – essentially embracing model formulations from across the full spectrum of hydrological model types. Recently, hydrological model ensembles have become more common. Most studies report the changes as an average over one or several time slices (10- to 30-year periods in the future) relative to the average of a reference period in the near past. Both, the time slice and the reference periods, vary strongly (Table 1).

Table 1 Approaches used in selected low flow studies on past trends and future changes.

Domain	Dataset/Source	Reference	Season distinction	Low flow index	Method/Model Experiment	Trend magnitude, Change metric	Time periods
Past changes: observations or modelled							
Multi-National Studies							
17 European countries	EWA	Stahl et al. (2010)	yes	AM(7)*	Regional Patterns	Sen slope in standard deviations	1962-2004, 3 longer ones
Europe (as part of global grid)	WATCH multi-model ensemble	Stahl et al. (2012)	yes	AM(7)	Regional Patterns from ensemble	Sen slope in % of mean over period	1963-2000
Scandinavia & Central Europe	EWA	Hannaford et al. (2013)	yes	AM(7)	MK Test	MK Test statistic for respective period	1930-2004 with varying start/ end
Nordic countries	Nordic countries' networks	Wilson et al. (2010)	no	AMD and AMV below Q70	MK Test (after pre-whitening)	positive/negative; significant/non-sign.	1920-2005, 1941-2005, 1961-2000
European Alps	AdaptAlp project	Bard et al. (2011)	"low flow year" def.	AM(1), AMD and AMV below Q85, start, centre and end	MK Test; field significance	positive/negative; significant/non-sign.	1961-2005
National-Scale Studies							
UK	Benchmark network	Hannaford & Marsh (2006)	no	AM(7), AM(30), Q70 prevalence, Q90 prevalence	Permutation test on slope, MK Test	Regression slope, Spearman's rank correlation	1963-2002, 1973-2002
	Benchmark network	Hannaford & Buys (2012)	yes	Seasonal Q95, Q70	Sen Slope	Sen slope in % of mean over period	1969 - 2008
France	French reference low flow network	Giuntoli et al. (2013)	"low flow year" def.	Drought severity below Q85	Rank correlation	positive/negative; significant/non-sign.	1968-2008
Germany	Various national networks (mostly those used for flood forecasting)	Kohn et al. (2013)	no	AM(1,7,21)	Sen slope, MK Test	Regression slope, Sen slope	1944 (or start of record)-2011
Austria	National network	Laaha et al. (2013)	yes	Q95	MK Test	Sen slope	1976-2009; 1951-2004 (and sub-periods)
Modelled future changes					Model/Scenario		
Global	Global Large Rivers (GRDC)	Hirabayashi et al. (2008)	no	Q90 prevalence	MIROC GCM/MATSIRO LSM, transient runds for 20C and SRES A1B for 2001-2100	Time slice change compared to 20C (days)	2001-2013; 2071-2100
Europe	0.5 degree grid	Lehner et al.(2006)	no	100y-drought (frequency of AMV below Qmedian (monthly))	WaterGAP, Delta change from A1B scenario of 2 GCMs, water use scenarios	Time slice change of return period compared to 1961-90	2020s and 2070s
	Entire River Network	Feyen & Dankers (2011)	yes	AM(1) and AMV belowQ80 (daily)	Lisflood, HIRHAM RCM, A2 scenario	Time slice change of indices for specific return periods	
National Scale Studies							
Norway, Glomma basin	1x1 km model grid	Wong et al. (2011)	yes	Max. drought duration and area below Q80	2GCMs, 1RCM, bias correction, HBV hydrol. model	TIme slice change to control 1961-1990	2071-2100
UK	Regionalised semi-distributed Hydrological model	Prudhomme et al. (2012)	yes (but not for low flow statistics)	Seasonal runoff, annual Q95	11-member perturbed physics ensemble (PPE) of an RCM nested within 11 member GCM PPE	Time slice change factors from control (1961 - 1990)	2050s
France	Grid/many gauging station points	Chauveau et al. (2013)	no	QMNA5***	7GCMs (AR4 runs), downscaling, 2 hydrological models	Time slice change to control 1961-1990	2050s
Austria	Catchments, then regionalized to river network with TopKriging	Blöschl et al. (2011)	yes	Q95	CLM derived delta change, catchment hydrological model	Time slice change compared to 1976-2007	2021-2050

* AM(n): annual n-day average minimum flow
**Annual max. streamflow drought duration and deficit volume below a threshold
***Annual monthly minimum flow with a 5 year return period

Global-scale hydrological modelling studies mostly look at changes in annual and monthly hydrological regimes of large rivers. Few have assessed low flows or streamflow drought specifically. The continental-scale studies listed in Table 1 calculated changes in streamflow drought return periods, reporting different aspects of future change relative to a reference period. National studies have mostly used the same low flow indices as in the observation-based studies of past changes (Table 1), i.e. a large diversity of specific low flow and streamflow drought indices. In addition, many climate change modelling experiments that specifically look at low flows have been carried out at smaller river basin scales (not shown).

LOW FLOW AND DROUGHT CHANGES IN EUROPE

Recent observed changes

The observation-based trend studies in Table 1 suggest that recent changes in low flows are easier to interpret when looking at distinct seasons or at specific hydrological regimes, i.e. records with similar low flow processes and seasonality. There seems to be consensus that winter low flows, which occur in snow-affected areas of Europe, have increased over the past decades. Winter low flows have also increased in northern and western regions with limited winter snow, as a result of increasing winter rainfall and runoff.

A reanalysis model experiment based on a bias-corrected forcing dataset and an ensemble of global hydrological models allowed the calculation of trends in seasonal flows and extremes for Europe (Stahl *et al*., 2012). Figure 1 shows the trends in summer climate (temperature and precipitation) and low flows over the modelling period 1962–2000. According to these simulations, low flows have decreased in southern Europe, parts of central and eastern Europe, Denmark, southern Norway, Sweden and in some areas of the UK. July and August temperatures have increased in all these regions suggesting an increase in evapotranspiration as a contributing cause. Some of the positive summer low flow trends coincide with regions that have seen precipitation increases in June and July.

Stahl *et al*. (2012) further showed that while trend patterns in observed low flow records are broadly similar to those in Fig. 1, there tends to be more spatial variability. However, many national scale studies do not confirm the negative low flow trend pattern in Fig. 1 or even report increasing summer low flows. Contrasting results include national studies in the UK and Germany (Table 1). One reason may be that the pan-European studies ended with the widespread summer droughts of 2003 and 2004, whereas national studies cover different periods, e.g. the more mixed

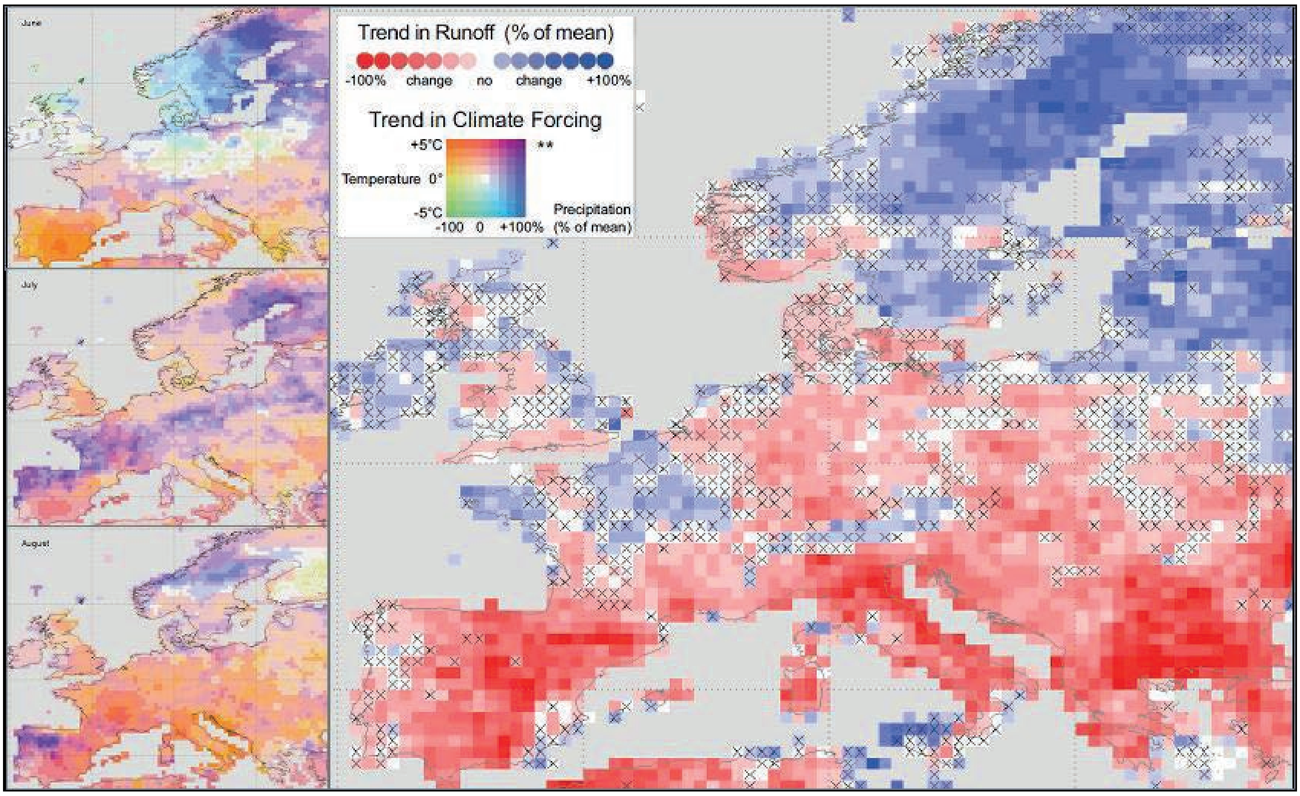

Fig. 1 Trends in summer hydroclimate and modelled low flows in Europe over the period 1962–2000. Left: precipitation and temperature trends from the WATCH forcing data (www.eu-watch.org/data_availability) for June, July and August. Right: Low flow (AM(7)) trends for the summer half-year from the WATCH multi-model ensemble (from Stahl et al., 2012). Crosses: <¾ of the models agree on the sign of the trend.

low flow results of Hannaford & Buys (2012) are based on a period ending with wet summers in 2007 and 2008. In the study by Kohn *et al.* (2013), the influence of low flow augmentation management schemes introduced in some regions may obscure climatic trends. In Austria, in contrast, negative low flow trends in the south appear to be relatively stable, independent of period, while trends elsewhere depend strongly on the period studied (Laaha, *et al*., 2013). In France, Giuntoli *et al*. (2013) found a consistent increase of drought severity in southern France over the 1968–2008 period, but when considering an earlier period (1948–1988) these trends were not apparent. However, correlations with climate indices remain stable, which suggests the evolution of low flows in France to be closely linked with multi-decadal climate fluctuations. Similarly, Hannaford *et al*. (2013) illustrate these high sensitivities to the period of record on a regional scale, which may be linked to changing atmospheric circulation patterns, e.g. the North Atlantic Oscillation (NAO) in Scandinavia.

Future changes

In global to continental-scale modelling studies with future climate change scenarios, the general climatic pattern of increasing precipitation in Northern Europe and decreasing precipitation in the South appears to dominate the literature and is reported in many summary reports for Europe. International studies dealing specifically with future low flows, however, are rare. There are only two pan-European studies on changes in streamflow drought characteristics (Table 1). Both find an exacerbation of streamflow drought in southern Europe and the UK, but differ somewhat in their assessments of the Alps, Eastern and Northern Europe. However, neither study considered the full range of uncertainty sources; in particular, they used only one hydrological model.

Many national studies project even more widespread decreases in summer low flows or increases in streamflow drought characteristics, some of them based on ensembles of GCMs, RCMs, and hydrological models (Table 1). For Norway, Wong *et al*. (2011) found an increase in hydrological drought duration and affected area in the southern and northernmost parts of the country, although changes in future meteorological drought characteristics were small. Based on a perturbed physics ensemble for the UK, and hence including some GCM uncertainty, Prudhomme *et al.* (2012) suggest a decrease in annual low flows, mainly driven by a decrease in summer flows. Whilst there is a large range in projections, future decreases in summer flow are one of the more consistent results from this study, compared with other seasons. Several catchment-scale impact studies in the UK (not shown) also found a dramatic decrease in Q95 and increase in failure to match water-demand management flow thresholds in the south of England as early as the 2050s. In France, Chauveau *et al*. (2013) similarly found a dramatic decrease in low flows over the whole of France for the 2050s. Specific studies for river basins (not shown), including the Garonne, Loire, Seine and Rhone rivers, estimated a 20–50% decrease in the national legal low flow threshold. In Austria, Blöschl *et al.* (2011) projected that the Q95 will increase in the Alps (winter), but will decrease in southern and southeastern Austria (summer).

DISCUSSION AND CONCLUSION

According to a number of different scenario modelling assessments at different scales in Europe, summer low flows are likely to decrease notably in the future, from the South of Europe all the way up to southern Norway. Observed trends in summer low flows during the past, however, are much less consistent and show both decreases and increases with rare statistical significance, although clear regional patterns can be detected. Observed changes are dependent on the data selected and on the time period analysed. Many national studies cover a period that starts in the 1960s or 1970s, consistent with the timing of widespread instrumentation of smaller basins, which tend to be less influenced by regulation and hence more suited for use in climate sensitivity studies. The start of this period coincides not only with the NAO shift, but also with more widespread river regulation such as the building of dams in mountainous areas. Regulation is poorly documented in many countries and therefore human influences present a challenge for low flow assessments, both with models and observations. Some observation-based studies have used data from near-natural reference networks, but most modelling, in particular for large rivers, needs to incorporate flow management and regulation. Whilst reference networks are vital for discerning climate signals, it is for managed and impacted rivers that the greatest utility is to be gained from projections. In addition, gradual changes in land use (e.g. afforestation) may influence the water balance and thus low flow. Hydrometric networks and datasets need to be improved with respect to metadata on these influences that may confound climate change attribution.

On the basis of this survey, a tentative ranking can be made of the importance of all methodological aspects on the assessment of past low flow changes: data and catchment selection criteria > considered season > selected time period > measure of change > low flow index. In other words, the choice of methodology for analysing changes and trends, such as the low flow index or trend test, appear to matter less than the initial data choices, thus highlighting the need for better data documentation. For model-based assessments of future changes, the knowledge base for a ranking is much smaller and ensemble approaches have only recently started to quantify the different sources of error and uncertainty. Forcing from GCMs exerts a dominant influence; with considerable differences between GCMs in projected climatic changes (particularly for precipitation), impacts on low flows vary considerably. Some first ensemble studies with multiple hydrological models suggest that the uncertainty from the use of different hydrological models can be high as well, especially for low flows – the part of the regime on which catchment characteristics tend to exert a major control, and where estimation of losses by evapotranspiration can have a strong influence on future change. Future work should address these aspects and also aim for better integration across different model types and spatial scales.

Acknowledgements Financial support came from: EU FP7 project DROUGHT-R&SPI (contract no. 282769); Austrian Climate Research Program's "CILFAD" Project.

REFERENCES

Blöschl, G., Viglione, A., Merz, R., Parajka, J., Salinas, J. & Schöner, W. (2011) Auswirkungen des Klimawandels auf Hochwasser und Niederwasser. *Österreichische Wasser- und Abfallwirtschaft* 63, 21–30.

Chauveau, M., Chazot, S., Perrin, C., Bourgin, P.-Y., Sauquet, E., Vidal, J.-P., Rouchy, N., Martin, E., David, J., Norotte, T., Maugis, P. & de Lacaze, X. (2013) What will be the impacts of climate change on surface hydrology in France by 2070? *Houille Blanche* 4, 5–15. doi: 10.1051/lhb/2013027.

Giuntoli, I., Renard, B., Vidal, J.-P. & Bard, A. (2013) Low flows in France and their relationship to large-scale climate indices. *Journal of Hydrology* 482, 105–118, doi: 10.1016/j.jhydrol.2012.12.038.

Hannaford, J. & Marsh, T. J. (2006) An assessment of trends in UK runoff and low flows using a network of undisturbed catchments. *Int. J. Climatol*. 26, 1237–1253. doi: 10.1002/joc.1303.

Hannaford J. & Buys G. (2012) Trends in seasonal river flow regimes in the UK. *J. Hydrol.* 475, 158–174. doi:10.1016/j.jhydrol.2012.09.044.

Hannaford, J., Buys, G., Stahl, K., & Tallaksen, L. M. (2013) The influence of decadal-scale variability on trends in long European streamflow records. *Hydrol. Earth Syst. Sci.* 17, 2717–2733, doi:10.5194/hess-17-2717-2013.

Kohn, I., Freudiger, D., Rosin, K., Stahl, K., Weiler, M. & Belz, J. U. (2013) Das hydrologische Extremjahr 2011: Dokumentation, Einordnung Ursachen und Zusammenhänge. – *Mitteilungen Bundesanstalt für Gewässerkunde* Nr. 29. (BfG), Koblenz (in press).

Laaha, G., Koffler, D., Haslinger, K., Schöner, W., Parajka, J. & Blöschl, G. (2013) Climate impacts on low flows and droughts - Exploring the link between low flows and climate for long-term trend analysis. In: *Climate Change Centre Austria CCCA und Klima- und Energiefonds gemeinsam mit Universität für Bodenkultur Wien*, Tagungsband 14. Klimatag – Klimawandel, Auswirkungen und Anpassung sowie Vermeidung, p. 30–31.

Prudhomme, C., Young, A., Watts, G., Haxton, T., Crooks, S., Williamson, J., Davies, H., Dadson, S. & Allen, S. (2012) The drying up of Britain? A national estimate of changes in seasonal river flows from 11 Regional Climate Model simulations. *Hydrol. Processes* 26, 1115–1118. doi: 10.1002/hyp.8434.

Soubeyroux, J.-M., Vidal, J.-P., Baillon, M., Blanchard, M., Céron, J.-P., Franchistéguy, L., Régimbeau, F., Martin, E. & Vincendon, J.-C. (2010) Characterizing and forecasting droughts and low-flows in France with the Safran-Isba-Modcou hydrometeorological suite. *Houille Blanche* 30–39. doi: 10.1051/lhb/2010051.

Stahl, K., Tallaksen, L. M., Hannaford, J. & van Lanen, H. A. J. (2012) Filling the white space on maps of European runoff trends: estimates from a multi-model ensemble. *Hydrol. Earth Syst. Sci.* 16, 2035–2047, doi: 10.5194/hess-16-2035-2012.

Stahl, K., Hisdal, H., Hannaford, J., Tallaksen, L. M., van Lanen, H. A. J., Sauquet, E., Fendekova, M., Jordar, J. (2010) Streamflow trends in Europe: evidence from a dataset of near-natural catchments. *Hydrol. Earth Syst. Sci.* 14, 2367–2382. doi: 10.5194/hess-14-2367-2010.

Wilson, D., Hisdal, H. & Lawrence, D.(2010): Has streamflow changed in the Nordic countries? – Recent trends and comparisons to hydrological projections. *J. Hydrol*. 394, 334–346. doi: 10.1016/j.jhydrol.2010.09.010.

Wong, W. K., Beldring S., Engen-Skaugen T., Haddeland I. & Hisdal H. (2011) Climate change effects on spatiotemporal patterns of hydroclimatological summer droughts in Norway. *J. Hydrometeor.* 12, 1205–1220. doi: 10.1175/2011JHM1357.1.