
Laize, C.L.R.; **Acreman, M.C.**; Schneider, C.; **Dunbar, M.J.**; **Houghton-Carr, H.A.**; Florke, M.; Hannah, D.M.. 2014 Projected flow alteration and ecological risk for pan-European rivers. *River Research and Applications*, 30 (3). 299-314. 10.1002/rra.2645

Projected flow alteration and ecological risk for pan-European rivers

Cédric L.R. Laizé[1, 3*], Michael C. Acreman[1], Christof Schneider[2], Michael J. Dunbar[1], Helen A. Houghton-Carr[1], Martina Flörke[2], David M. Hannah[3]
1 Centre for Ecology and Hydrology, Maclean Building, Crowmarsh Gifford, OX10 8BB, UK
2 Center for Environmental Systems Research, University of Kassel, Kassel, Germany
3 School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK
* clai@ceh.ac.uk

Abstract

Projection of future changes in river flow regimes and their impact on river ecosystem health is a major research challenge. This paper assesses the implications of projected future shifts in river flows on in-stream and riparian ecosystems at the pan-European scale by developing a new methodology to quantify ecological risk due to flow alteration. The river network was modelled as 33,668 cells (5' longitude x 5' latitude). For each cell, modelled monthly flows were generated for an ensemble of 10 scenarios for the 2050s, and for the study baseline (naturalised flows for 1961-1990). These future scenarios consist of combinations of two climate scenarios and four socio-economic water-use scenarios (with a main driver of economy, policy, security, or sustainability). Environmental flow implications are assessed using the new Ecological Risk due to Flow Alteration (ERFA) methodology, based on a set of Monthly Flow Regime Indicators (MFRIs). Differences in MFRIs between scenarios and baseline are calculated to derive ERFA classes (no, low, medium, high risk), which are based on the number of indicators significantly different from the baseline. ERFA classes are presented as colour-coded pan-European maps. Results are consistent between scenarios and show European river ecosystems are under significant threat with about two-third at medium or high risk of change. Four main zones were identified (from highest to lowest risk severity): (i) Mediterranean rim, southwest part of Eastern Europe, and Western Asia; (ii) Northern Europe, northeast part of Eastern Europe; (iii) Western and Eastern Europe; (iv) inland North Africa. Patterns of flow alteration risk are driven by climate-induced change, with socio-economics a secondary factor. These flow alterations could be manifested as changes to species and communities and loss of current ecosystem functions and services.

Keywords ecohydrology; hydroecology; river ecosystem; flow alteration; ecological risk; climate change; socio-economic change; Europe

1 Introduction

Multiple factors determine the health of a river ecosystem (Norris and Thoms, 1999; Webb *et al.*, 2008; Moss, 2010), including light, water temperature, nutrients, discharge, channel structure, physical barriers to connectivity, species interactions and management practices (e.g. weed cutting, dredging, fish stocking). Many of the natural factors are interdependent (Vannote *et al.*, 1980; Rosenfeld *et al.*, 2007) and anthropogenic factors often co-vary (47% of 9,330 European river sites were found to be impacted by multiple pressures; Schinegger *et al.*, 2011). Ultimately, freshwater ecosystems are subjected to pressures produced by complex interactions between natural and human factors (Grantham *et al.*, 2010; Hart and Calhoun, 2010).

Discharge (i.e. flow, measured as a volume per unit time) is a key habitat variable, which changes dynamically in space and over time (Bunn and Arthington, 2002; Monk et al., 2008a). In addition to natural variations, river discharge may be influenced heavily by anthropogenic activities, such as water abstraction, storage in reservoirs and effluent returns, all associated with public supply, agriculture and industry. Several authors have suggested that many elements of the river flow regime, such as magnitude, variability and timing can influence freshwater ecosystems (Junk *et al.,* 1989; Richter *et al.,* 1996; Poff *et al*., 1997; Biggs *et al*., 2005; Arthington *et al.*, 2006; Kennen *et al*., 2007; Monk *et al*., 2008b). For example, the loss of wet-dry cycles and the stabilisation of water levels reduce the growth and survival of native aquatic macrophytes and favour invasive macrophytes (Bunn and Arthington; 2002). Further examples of the ecological impact of flow regime changes have been collated by Richter *et al*. (1998); while Bunn and Arthington (2002), Lytle and Poff (2004), Bragg *et al.* (2005) and Poff and Zimmerman (2010) provide comprehensive reviews of the literature.

Most flow–ecology studies have been based on the 'natural flow paradigm' (Poff et al., 1997), which uses the unaltered flow regime as the baseline reference condition and assumes any departure from 'natural' will lead to ecological change. Change can be interpreted in terms of impacts on living organisms (see references above) and/or more generally in terms of loss of ecosystem functions or services. For example, a change in flow regime causing a decrease in fish population also has an impact on fish-related ecosystem services, that is food provision and recreation (Okruszko et al, 2011). The functional relationship between flow alteration and ecological impact can take many forms (Arthington *et al.*, 2006); but is normally a linear (or curvilinear) response, or a threshold response/step function (Poff *et al*. 2010). For the latter, there are clear threshold responses (e.g. overbank flows needed to support riparian vegetation or to provide fish access to floodplain); but, for the former, critical points may need to be defined by expert judgement (Biggs and Rogers, 2003; Arthington *et al.*, 2004; Richter *et al.*, 2006). Many ecosystems have a high capacity to absorb disturbances without significant alteration, consequently some ecosystem functions and services may be restored by re-introducing certain flow regime elements, whereas for other functions, the ecosystem may be pushed beyond its resilience limits and may change to a new irreversible state. The resilience of ecosystems was conceptualised by Holling (1973) and has been subsequently applied widely (for a recent example relevant to rivers see Robson and Mitchell, 2010).

The Millennium Ecosystem Assessment (MEA; 2005) shows that many water-dependent ecosystems are being degraded or lost, with freshwater systems suffering due to withdrawal of water for human needs and fragmentation/ loss of connectivity due to regulatory structures (Nilsson *et al*., 2005). River discharge is anticipated to change in the future and it is estimated currently that habitats associated with 65% of 'continental discharge' are at risk worldwide (Vörösmarty *et al.* 2010). Similarly, Schinegger *et al*. (2011) found that of 9330 European river sites, 41% had altered hydrology and 35% altered morphology. In this context, this paper addresses the pressing need to better quantify broad scale future risks to European river ecosystems due to flow regime alterations and thus yield robust information to formulate European water policies.

This study was undertaken as part of the European Union (EU) SCENES (water SCenarios for Europe and for NEighbouring States) project. SCENES was a four-year Integrated Project under the EU 6th Framework, which investigated the future of freshwater resources up to the 2050s in 'Greater' Europe (defined as EU countries and neighbours i.e. Iceland, Norway, Belarus, Ukraine, Moldova, Turkey, non-EU Balkan countries, and Switzerland) and including the Mediterranean rim countries of north Africa and the near East, from Caucasus to the White Sea (see Figure 1). Innovatively, the project considered both climate-induced future change and also scenarios integrating socio-economic and policy drivers. SCENES provided a reference point for long-term strategic planning of pan-European freshwater. SCENES investigated impacts on different water use sectors (industry, food, energy, recreation, domestic use etc.); this paper focuses on impacts on water for the environment (Duel and Meijer, 2011).

The overall aim of this paper is to project the risks to European river ecosystems caused by river flow regime change under possible future climate and socio-economic/ policy scenarios. This aim is achieved through four objectives:

1. To quantify the degree of flow regime alteration in terms of ecologically relevant hydrological indicators
2. To identify spatial patterns of these indicators in the pan-European study area
3. To assess the consistency of these patterns across the different scenarios
4. To identify the main drivers of these patterns

There are few studies in the scientific literature addressing future ecologically relevant flow regimes and most focus on a limited number of sites and/or a limited geographical extent, and are often descriptive rather than quantitative. As highlighted by Heino et al (2009), there are many more papers on the impact of climate change on terrestrial biodiversity than on freshwater, and results about the latter tend to be for a small number of organisms, ecosystems, or regions. For example, the impact of climate change on macro-invertebrates in two UK rivers was investigated by Wright *et al*. (2004) while Graham and Harrod (2009) focused on fish in Britain and Ireland. More comprehensive analyses of climate impact on all aspects of freshwater ecosystems have been published with varying geographical extents: local (Johnson *et al*., 2009); UK-wide (Clarke, 2009; Wilby et al., 2010); regional (northern regions; Heino et al., 2009). Döll and Zhang (2010) undertook a worldwide study of future ecologically relevant flows, using a broad-scale gridded model with a cell resolution of 30’ x 30’ (about 55 x 55 km^2 at the equator, i.e. 3,025 km^2) and flow statistics that were a broad summary of the flow regimes (e.g. long-term annual averages). This paper is the first assessment of river ecological risk due to flow alteration: (i) to provide pan-European geographical coverage, (ii) to use a detailed (given the geographical extent) river network based on 33,368 cells with a 5’ x 5’ resolution, (iii) to consider explicitly a set of ecologically-relevant hydrological indicators (i.e. all facets of the flow regime), and (iv) to consider not just climate-induced change, but combined climate and socio-economic pressures.

2 Data and Methods

The research methodology includes five main components (as numbered in Figure 2): (1) climate data (observed historical and modelled future) used on their own or linked with (2) a set of socio-economic scenarios within (3) a large-scale hydrological and water use model (WaterGAP) to produce (4) sets of monthly flow time series (baseline and future) that serve as inputs for (5) the new Ecological Risk due to Flow Alteration (ERFA) screening method that compares future flows against baseline flows. The following sections detail each component. Notably, the selection of climate data and the development of the socio-economic scenarios (i.e. components 1 and 2) was carried out by a pan-European panel (PEP) of experts following the Story-And-Simulation (SAS) approach (Alcamo, 2008) by which narrative storylines of plausible futures and modelling work are linked iteratively within a participatory process.

2.1 Observed historical and modelled future climate data

Observed historical climate data for the reference period 1961-1990 were collated from the Climate Research Unit (University of East Anglia, UK). Projected future climate data for the period 2040-2069 (i.e. '2050s') were taken from two Global Circulation Models (GCMs): (i) IPSL-CM4, Institut Pierre Simon Laplace, France ('IPCM4' thereafter), and (ii) MIROC3.2, Center for Climate System Research, University of Tokyo, Japan ('MIMR' thereafter). These two GCMs were chosen after comparing nine GCMs from the IPCC Fourth Assessment (IPCC, 2007); they were considered representative of the variability between GCMs (Bärlund, 2010). For both GCMs, the IPCC SRES A2 emission scenario (IPCC, 2007) was selected; it describes a very heterogeneous world with high population growth, slow economic development and slow technological change (global greenhouse gas emissions projected to grow steadily during the whole 21st century and possibly to double by 2050 compared to the year 2000). Under SRES A2, IPCM4 predicts a high temperature increase and a low precipitation increase/decrease ("warm and dry") while MIMR predicts a high temperature increase and a high precipitation increase or a low decrease ("warm and wet"). Climate change scenarios were selected by PEP to be consistent with their socio-economic narrative storylines (see below).

2.2 Socio-economic scenarios

The PEP defined four different visions of future pan-European freshwaters (taking into account socio-economic and environmental settings, and possible consequences for water quantity and quality) up to the year 2050 described as narrative storylines (i.e. qualitative), which were then turned into quantitative scenarios based on Fuzzy sets and modelling results according to the SAS approach:

- Economy First (EcF), economy-oriented towards globalisation and liberalisation with intensified agriculture and slow diffusion of water-efficient technologies;
- Fortress Europe (FoE), closed-border Europe concentrating on common security issues with food and energy independence as the main focus of the European coalition;
- Policy Rules (PoR), stronger coordination of policies at the European level, driven in part by high energy costs and reduced access to energy supplies, expectation of climate change impacts and increasing water demand;
- Sustainability Eventually (SuE) transition from globalising, market-oriented Europe to environmental sustainability with quality of life as a central point.

The detailed methodology for the socio-economic scenarios is provided by Kok *et al.* (2010), Kok & van Vliet (2011) and Kok *et al.* (2011).

2.3 WaterGAP model

The continental-scale water model WaterGAP (Water – Global Assessment and Prognosis) is a semi-distributed water resource model consisting of two main components: a global hydrological model (Alcamo *et al.,* 2003; Döll *et al.,* 2003) to simulate the terrestrial water cycle and a global water use model (Döll and Siebert, 2002; Flörke and Alcamo, 2004; aus der Beek *et al*., 2010) to estimate water withdrawals and water consumption of five sectors (domestic, electricity production, manufacturing industry, irrigation, and livestock). This study used WaterGAP version 3.1 that performs its calculations on a on a 5' x 5' grid (i.e. about 6 x 9 km^2 in central Europe). This version has been used in a variety of recent studies, e.g. Ozkrusko *et al.* (2011) - wetland ecosystem services; Schneider *et al.* (2011a) - floodplain wetlands and (2011b) - bankfull flows and Flörke *et al.* (2011) - power plant water needs. Built into the model are 590 European dams from the European Lakes and Reservoir Database (ELDRED2, EEA) including management rules (Hanasaki *et al.*, 2006) to account for human alteration of water storage and transfer. WaterGAP calculates daily water balances for the land areas and open freshwater bodies for each individual grid cell then runoff from each cell is routed as river discharge along the modelled drainage network. Natural cell discharge is then reduced by consumptive water uses as calculated by the water use component of WaterGAP. The model is calibrated and validated independently against measured annual discharge data from the Global Runoff Data Centre (GRDC) at 221 gauging stations across Europe (Döll *et al.,* 2003).

For the present study, a subset of the WaterGAP cells was selected corresponding to all major European rivers and their tributaries (excluding tributary cells with fewer than 20 upstream cells due to limiting computer resources), thus totalling 33,368 cells (for example, see Figure 3). These cells are the outlets of as many basins and nested sub-basins, with the smallest basin represented being 63 km^2.

2.4 Model runs

In total, eleven sets of modelled monthly flow series were generated using different combinations of climate data inputs and socio-economic scenarios. Naturalised flows for 1961-1990 were generated by running WaterGAP with the hydrological component only (i.e. no water usage) and the historical climate data from CRU as input. This naturalised run is the baseline for the subsequent analysis (termed 'Baseline'). In addition, ten model runs representing future flows under various water usage conditions were generated: five runs for each GCM (termed 'IPCM4' and 'MIMR'; see above), including one for naturalised flows (termed 'Natural') and one for each of the four socio-economic scenarios (termed 'EcF', 'PoR', FoE', 'SuE'; see above). For all projected runs, the period of record is 2040-2069 (termed the '2050s').

2.5 Ecological Risk due to Flow Alteration (ERFA) screening method

The new ERFA screening method was based conceptually on the Range of Variability Approach (RVA) using Indicators of Hydrological Alteration (IHA), a technique for defining ecologically appropriate limits of hydrological change introduced by Richter *et al*. (1996, 1997). The underlying assumption of the IHA/RVA is that, if a river ecosystem exists under given baseline hydrological conditions, then any impact causing departure from these baseline conditions, beyond some thresholds, will alter the ecosystem. Example impacts could be: the building of a hydraulic structure, the creation of an abstraction point or, as in the present study, climate and socio-economic change. The IHA/RVA recognises that all characteristics of the flow regime—their magnitude, duration, timing, frequency and rate of change—are ecologically important.

ERFA relies similarly on a series of indicators describing the flow regimes, which are calculated for the baseline (i.e. naturalised flows 1961-1990) and for every future projection.

Presenting the results of the departure from baseline of every single indicator would involve displaying a very large amount of information so to enable ready interpretation, the ERFA method aggregates information as a simple colour-coded risk classification based on how many indicators differ from the baseline by more than a set threshold.

The IHA are based on 32 different variables derived from daily flow statistics (one value per year of record) as shown in Table 1; the IHA themselves are indicators of the magnitude and variability of the variables, derived for for the pre-and post-impact periods (or baseline and future periods in this study).Given this study focuses on an extensive pan-European river network (>33,368 sites) and 30-year long records, there is a significant cost (mostly computing time) in using the daily IHA as the basis for deriving ERFA classes. Therefore, the approach was adapted to use monthly flow statistics, thereafter referred to as Monthly Flow Regime Indicators (MFRIs). This also provides a methodology for wider application when only monthly data are available, which is common. For testing purposes, two versions of the ERFA method were implemented using the MFRIs (MFRI/ERFA) and the IHA (IHA/ERFA) and were compared for a subset of 683 WaterGAP grid cells (Figure 2). The following section gives background on the IHA, details the development of the MFRIs, and of both ERFA implementations, and gives the results of their comparison. Note: in this study, river flow data (m^3s^{-1}) were converted to runoff (mm) to allow ready comparison across all basins of different sizes.

2.5.1 Defining the MFRI variables

A summary of the original 32 daily time-step variables is given in Table 1. The list of nine monthly time-step variables (listed in Table 2) was selected to maintain a similar structure of regime characteristics and by taking into account:

- Redundancy within the 32 IHA variables due to their interdependence; information from the published literature (Olden and Poff, 2003; Monk *et al*., 2007) was supplemented by a rank-based correlation analysis (*tau;* Kendall, 1938) applied to the test subset of 683 sites
- Daily variables not computable at the monthly time step by definition (e.g. 1-day minimum or maximum flows) or less meaningful (e.g. rates of rise between months only showed seasonal patterns year after year)
- Expert ecological knowledge (e.g. Acreman *et al*., 2008)

2.5.2 Indicators

The hydrological variables (one value per year of record per site) are used to derive indicators capturing the magnitude and variability of each variable as one value across the whole period of record for each site or cell. Magnitude could be described by the mean or the median (i.e. 50th percentile), and the variability by the standard deviation or the interquartile range (IQR; i.e. difference between 75th and 25th percentiles) of annual variables (Richter *et al*., 1997). In this study, the median and the IQR were chosen because: (i) they are less sensitive to outliers than mean and standard deviation and (ii) they better describe the hydrological variables that are not normally distributed. An exception was made for monthly-based flood and minimum flow timing variables; these variables are the months (i.e. integers ranging from 1 to 12) when flood and low flow events happen and, given their discrete range of values, they were found more meaningfully summarised by their mode. The indicators were derived as follows:

- Based on daily flow data: 64 indicators (32 medians and 32 IQR) based on the 32 IHA variables
- Based on monthly flow data: 16 indicators (i.e. the MFRIs; seven medians, seven IQR, and two modes) based on the nine MFRI variables (see Table 2)

2.5.3 Thresholds and derivation of ERFA classes

Indicators were computed for the baseline data and for all modelled scenarios, then absolute differences between indicators for each scenario and those for the baseline are calculated. Based on expert knowledge (e.g. Acreman *et al*., 2008), indicators are considered as departing significantly from the baseline if:

- median or IQR indicators are more than 30% different from the baseline
- mode indicators are more than 1 month different

For practicality, ease of display and interpretation, differences were aggregated via a colour-coding system: a cell is assigned blue (no risk) green (low risk), amber (medium risk), or red (high risk) when its number of indicators differing from the baseline is:

- 0, 1–20, 21–40, and 41–64, respectively (IHA)
- 0, 1–5, 6–10, or 11–16, respectively (MFRIs)

2.5.4 Method testing

The MFRI/ERFA and IHA/ERFA implementations were compared for the subset of 683 WaterGAP cells (Figure 2) representing sites located along major rivers (approximately one site for every 100 km stretch of river). For those daily variables analogous to monthly variables (see Table 2) results were similar (e.g. monthly mean flows) or in the same range (e.g. Julian dates falls within the same period as the mode of month). Across all model runs, 60-70% of the sites obtain the same colour code. For 10-20% of sites the IHA/ERFA indicated more severe risks, and for 5-15% of sites less severe risks, than the MFRI/ERFA. Overall, the IHA/ERFA tends to give slightly higher risks, which is consistent with daily variables giving a more detailed description of the hydrological regime. However, for the majority of sites, the results were the same regardless of time step. Hence, the MFRI/ERFA method was retained as it is suitably informative for the scope of this study.

3 Results

This section identifies the key patterns in departure of the 16 individual MFRIs from the baseline (*3.1 Hydrological indicator patterns)* and then moves on the ERFA for the 10 model runs by: (i) mapping and comparing the overall breakdowns of ERFA classes (*3.2 Breakdown of future ERFA*); (ii) mapping and comparing the geographical location of the risks (*3.3 ERFA spatial patterns*); and (iii) mapping synthesized results to show where risks are spatially consistent across all model runs (*3.4 Commonality of impacts across all model runs*).

3.1 Hydrological indicator patterns

In accordance with the intended method development, all indicators show varying degrees of departure from the baseline and thus play an active role in the overall ERFA. However, some indicators seem more sensitive than others. Low flow indicators are dominated clearly by the

IQR of the number of months below threshold (indicator 13), that is by the variability of low pulses. Figure 3 box plot shows for all 16 MFRIs (identified by their number from Table 2 and grouped by hydrological type) the percentage of cells (out of 33,368) differing from the baseline across the ten model runs. High flow indicators are dominated by the median of the number of months above threshold (indicator 1) and its IQR (indicator 2), that is the magnitude and variability of high pulses. For the seasonal flow indicators, the median/IQR of the mean January flow (indicators 4/5), and of the mean April flow (indicators 6/7) show higher percentages than median/IQR of July and October (indicator 8/9 and 10/11, respectively) so that winter and spring flows seem to dominate over summer and autumn flows.

3.2 Breakdown of future ERFA

The picture of future ERFA classes is very consistent between model runs with the different socio-economic scenarios giving similar results and the main differences being between: (i) climate models - see IPCM4 Natural (Figure 4) vs. MIMR Natural (Figure 5) and IPCM4 vs. MIMR socio-economic runs (Figure 6); and (ii), Natural runs and socio-economic runs - see IPCM4 Natural (Figure 4) vs. IPCM4 socio-economic runs (Figure 6) cf. similarly for MIMR (Figure 5 vs. Figure 6). Regardless of scenario, 54–55% of the cells (out of 33,368) are in the medium risk class, and 14–20% in the high risk class (Table 3). In terms of the difference between climate models, IPCM4 runs have slightly more high risk cells (16–22%) than MIMR runs (14–17%); whereas MIMR runs have slightly more low risk cells (24–26%) than IPCM4 (18–25%). For both climate models, the socio-economic runs have more high risk and fewer low risk cells than the corresponding Natural run, although this is more subtle for MIMR (difference of 0–3% for high risk, 1–2% for low risk) than for IPCM4 (4–6% for high risk, 5–7% for low risk). As noted above, socio-economic runs are similar but these can be ranked (Table 3), for both climate models, by decreasing risk severity as EcF (highest risk), FoE, PoR, and SuE (lowest risk).

3.3 ERFA spatial patterns

Although the total numbers of WaterGAP cells within each ERFA class are very similar between model runs, the underlying spatial distribution of risk locations differs between model runs. As in Section 3.2, the main differences are between: (i) climate models - see IPCM4 Natural vs. MIMR Natural in Figure 7, which shows where ERFA are the same for both runs (green), and where MIMR is less severe (blue) and more severe (red) than IPCM4 and (ii), Natural and socio-economic runs - see Natural runs vs. their respective socio-economic runs in Figure 8, which shows where ERFA classes are the same (green), and different (red).

Between climate models, MIMR runs are generally about one-third different from IPCM4. Table 4 summarises the percentage of the cells (out of 33,368) that have different ERFA classes when comparing runs against each other (e.g. IPCM4 Natural differs from MIMR Natural for 36% of the cells). Runs for socio-economic scenarios differ from the Natural run by 17–21% for IPCM4 and 3–9% for MIMR. Differences between socio-economic scenarios are 4–8% under both IPCM4 and MIMR. The relative difference between socio-economic runs is the same for both climate model. EcF runs show the greatest departure from Natural runs, followed by FoE, PoR and SuE (least different from Natural).

There is no distinct geographical pattern across Europe in terms of the differences in risk between climate models. However, the socio-economic scenarios cause locational changes along an east-west 'belt', which is marked especially for IPCM4 runs and consistent for MIMR runs although somewhat less well-defined (Figure 8).

3.4 Commonality of impacts across all model runs

Based on the overall agreement between the ten model runs, four main zones can be identified: (i) highest risk - the Mediterranean rim (bulk of Southern Europe and coastal region of North Africa), the southwest part of Eastern Europe, and Western Asia; (ii) medium/high risk, Northern Europe (including Iceland) and northeast part of Eastern Europe; (iii) low/medium risk, Western and Eastern Europe (including Ireland and UK); (iv) lowest risk, inland region of North Africa. Figure 9 provides a summary map in which cells with the same ERFA class for all 10 runs are allocated the given class (i.e. 'None', 'Low', 'Medium', 'High'), cells with either of two adjacent ERFA classes are designated a joint class (i.e. 'None/Low', 'Low/Medium', and 'Medium/High'), and remaining cells that are inconsistently classified are labelled 'Mixed'.

4 Discussion and Conclusion

As highlighted in the Introduction, there are few studies focusing on future ecologically-relevant flow regimes, and existing studies are often either descriptive and/or have limited geographical scope (Wright *et al*., 2004; Clarke, 2009; Graham and Harrod, 2009; Heino *et al*., 2009; Johnson *et al*., 2009; Wilby *et al*., 2010). The only thematically analogous paper to this study is by Döll and Zhang (2010), although their approaches varies markedly (worldwide geographical extent, much coarser grid resolution, less detailed river network, fewer and broader scale hydrological variables, and lack of integrated climate/socio-economics). This study provides the first, detailed pan-European systematic assessment of future effects of climate and socio-economic change on ecologically-relevant river flow indicators by developing the new ERFA methodology.

4.1 Model run inter-comparison

Patterns are reasonably consistent across model runs. However, there are notable differences between climate models and socio-economic scenarios related mainly to the location of risks. In terms of the breakdown of ERFA classes, no socio-economic scenario mitigates climate-induced risks since all socio-economic runs have a few more medium and high risk cells than the Natural runs (see Table 3). Although the results of socio-economic scenarios are very similar, subtle differences are noteworthy. Ranking by risk severity shows that highest risks are under EcF, whereas SuE show least risk. This is consistent with the narrative storylines whereby EcF is the market-driven scenario as opposed to SuE that is the environment-driven scenario, i.e. the 'greenest' of all (Kok *et al.,* 2010). In terms of ERFA class location, there is again a strong similarity between socio-economic scenarios; the most notable difference is between the Natural runs and their respective socio-economic runs as shown in Figure 8. Location shifts in ERFA classes for the different socio-economic scenarios occur in a broad east-west swath across the mid-continental Europe. It may be hypothesised that this zonal area corresponds to the more populated and/or more managed areas where changes in socio-economic changes may be more apparent. It is noteworthy that given the geographical extent of the study and the WaterGAP grid resolution (i.e. 33,368 5' x 5' cells) even a few percentage points difference in cell impacts can translate into several hundreds km of river.

4.2 Spatial patterns and coherence between model runs

Using the new ERFA methodology developed in this study, more than two thirds of the river network (Greater Europe, Near East, North Africa) is at medium or high risk, regardless of the climate model or scenario used. Thus, European river ecosystems are under significant threat in the future. This is likely to be manifested in changes to species and communities and loss of current ecosystem functions and services (Poff and Zimmerman, 2010; Okruszko et al, 2011). Broad regions with contrasting impact levels have been identified (Figure 9). The least impacted region is the lower half of North Africa, which has low population (hence low water demand). Focusing on the other, more densely populated, regions, Western and Eastern Europe is the least impacted, while the Mediterranean rim extending up to Western Asia is the most impacted. It could hypothesised that this is due to the climatology of temperate oceanic regions being less affected by climate change than semi-arid/continental locations (Kundzewicz *et al*., 2008).

4.3 Identifying the main driver

The results show that climate is the primary driver of change by 2050 under the modelled conditions and climate sets the broad patterns at the pan-European scale. In a previous study on a groundwater and river resources management programme at a European scale (GRAPES; Acreman *et al*, 2000; Acreman, 2001), the impact of current anthropogenic pressures, such as water abstraction, outweighed the then projected impacts of climate (this may be partly due to the focus of GRAPES on case studies of heavily impacted basins in the UK, Spain and Greece). In contrast, this study shows that climate change impacts dominate over water use impacts at a general level across Europe, while socio-economics is a secondary driver. However, this finding has to be set within the context of the current approach: in WaterGAP, water consumption (i.e. abstracted minus return flows) is lumped at the cell level because the locations of flow abstractions and returns within a cell are not known; this value is relatively low for domestic and industrial usage.

Generally, basin properties act as modifiers of climatic inputs (Laize and Hannah, 2010). The WaterGAP model captures this by using physical characteristics at cell level (e.g. elevation, slope, land use, geology; Döll and Flörke, 2005). Physical characteristics therefore influence, by design, the modelled flows used in this study, and consequently the ERFA classes based on those. The downstream aggregation of information by cell routing along the drainage network makes it difficult to state from the model specifications what this influence is at the basin scale. Exploratory analysis suggests that some broad basin types have higher ERFA than others but a full analysis of the influence of basin properties is beyond the scope of this paper, hence a subject for future research.

4.4 Further research and wider implications

The ERFA methodology assesses the absolute departure of the MFRIs from the Baseline. Indicator departure can be due to increase/decrease (e.g. magnitude, duration), or advance/delay (timing). The actual effect on given species or ecosystem services depends on the type of flow (i.e. low, seasonal, or high) being altered and how alteration manifest (e.g. high flows affecting floodplain inundation, migration and channel maintenance, seasonal flows affecting habitat availability for growth and over-wintering, low flows affecting habitat availability for the young) and on the target organism or service. For example, less variable flows benefit macrophytes, whereas higher flow magnitudes may be detrimental to macrophytes (Bragg *et al,* 2005); a change in high flow timing may causes a loss of cue for fish with synchronised spawning or migration (Bunn and Arthington, 2002), or for plants and their seed release (Lytle and Poff, 2004). Some ecological responses are the same whether flow indicators are decreasing or increasing. For example, lower or higher magnitudes in extreme high or low flows cause altered assemblages and reduced diversity (Poff and Zimmerman, 2010). In that regard, the present approach should be seen as a screening tool to identify systematically regions of potential impact on which to focus further hydroecological research attention (e.g. Piniewski *et al*., 2012).

It would be useful to relate the departure from the baseline hydrological regime to ecological impacts beyond the qualitative rules collated in the literature. Using historical observed data can provide a way to (semi-)quantify these impacts (e.g. broad-scale fish species richness and mean annual flow; Xenopoulos et al, 2005). However, this is complicated by: (i) the fact that flow, although a key variable, is not the only factor affecting river ecosystems (e.g. water temperature has a major influence – Caissie, 2006); (ii) the general mismatch in nature and spatio-temporal scales of hydrological and ecological datasets (Monk *et al.*, 2008a); and (iii) monitoring generally not focusing specifically on ecological responses to flow alterations (Souchon et al, 2008).

The ERFA methodology could used in relation to the European Water Framework Directive (WFD; European Commission, 2000), which requires EU Member States to achieve and maintain at least 'Good Ecological Status' (GES) in all rivers by 2015. Although flow-based criteria are not used directly to assess GES, it has been recognised that restoration or maintenance of the flow regime is often one of the measures needed to ensure GES and can be set in the River Basin Management Planning process (Acreman and Ferguson, 2010). The present study identifies rivers potentially more susceptible to fail GES due to flow alteration.

More generally, river restoration requires reference conditions to set-up appropriate outcome targets (e.g. Nestler et al., 2010; Stoddard et al., 2006; Palmer et al., 2005), which traditionally relate to past ecological state. However, under changing water availability, whether due to water use or climate, reverting to such reference conditions may be too restrictive as it does not take into account the natural variability of the system (see Overton and Doody, 2012). The present study could be used to identify appropriate conditions as targets for restoration in the context of changing climate and socio-economic conditions across Europe.

4.5 Concluding remark

This paper is the first assessment of river ecological risk caused by the alteration of flow regimes: (i) having a pan-European geographical coverage, (ii) using a detailed river network, (iii) considering a set of ecologically-relevant hydrological indicators, and (iv) combined climate and socio-economic/policy scenarios. With regards to the four objectives of the study:

1. Two thirds of the European rivers are at medium or high ecological risk by 2050s.
2. ERFA classes were mapped and four main zones were identified (Mediterranean rim, southwest part of Eastern Europe, and Western Asia; Northern Europe, northeast part of Eastern Europe; Western and Eastern Europe; inland North Africa).
3. All model runs yield very consistent patterns in terms of breakdowns of risk classes; the main difference relates to the geographical location of the risks.

4. Patterns are primarily driven by climate, with socio-economics being a secondary driver.

This study provides a screening tool to identify systematically which pan-European regions are more at risk in order to better focus further hydroecological research attention.

Acknowledgements

The authors gratefully acknowledge financial support for the project water SCenarios for Europe and NEighbouring States (SCENES) from the European Commission (FP6 contract 036822), and from the Natural Environment Research Council (NERC) through its National Capability funding to the Centre for Ecology and Hydrology. The views expressed in the paper are those of the authors, and not necessarily of the coordinating or funding bodies of the SCENES project.

References

Acreman MC. 2001. Towards the sustainable management of groundwater-fed catchments in Europe. In *Regional management of water resources,* Schumann AH, Acreman MC, Davis R, Marino MA, Rosbjerg D, Xia Jun (eds). IAHS: Wallingford, UK. No. 268.

Acreman MC, Ferguson A. 2010. Environmental flows and European Water Framework Directive. *Freshwater Biology* **55**: 32-48

Acreman MC, Almagro J, Alvarez J, Bouraoui F, Bradford R, Bromley J, Croke B, Crooks S, Cruces J, Dolz J, Dunbar M, Estrela T, Fernandez-Carrasco P, Fornes J, Gustard A, Haverkamp R, de la Hera A, Hernández-Mora N, Llamas R, Martinez L, Papamastorakis J, Ragab R, Sánchez M, Vardavas I, Webb T. 2000. *Technical Report. Report to the European Commission ENV4 - CT 95 – 0186 – Groundwater and River Resources Action Programme on a European Scale (GRAPES).* Institute of Hydrology: Wallingford, UK

Acreman MC, Dunbar MJ, Hannaford J, Wood PJ, Holmes NJ, Cowx I, Noble R, Mountford JO, King J, Black A, Extence C, Crookall D, Aldrick J. 2008. Developing environmental standards for abstractions from UK rivers to implement the Water Framework Directive. *Hydrological Sciences Journal* **53**(6): 1105–20.

Alcamo J. 2008. The SAS Approach: Combining Qualitative and Quantitative Knowledge in Environmental Scenarios, Chapter 6. In *Environmental Futures: The Practice of Environmental Scenario Analysis*, Alcamo J. (ed). Elsevier; 123–148.

Alcamo J, Döll P, Henrichs, T, Kaspar, F, Lehner, B, Rösch, T, Siebert, S. 2003, Development and testing of the WaterGAP 2 global model of water use and availability. *Hydrological Sciences Journal* **48**(3): 317–337.

Arthington AH, Tharme R, Brizga SO, Pusey BJ, Kennard MJ. 2004. Environmental flow assessment with emphasis on holistic methodologies. In *Proceedings of the Second International Symposium on the Management of Large Rivers for Fisheries Volume II,* Welcomme, R, Petr T (eds). FAO Regional Office for Asia and the Pacific, Bangkok, Thailand. RAP Publication 2004/17, pp. 37–65.

Arthington AH, Bunn SE, Poff NL, Naiman RJ. 2006. The challenge of providing environmental flow rules to sustain river ecosystems. *Ecological Applications* **16**: 1311–1318.

Aus der Beek T, Flörke M, Lapola DM, Schaldach R, Voß F, Teichert E. 2010. Modelling historical and current irrigation water demand on the continental scale: Europe. *Advances in Geosciences* **27**: 79–85. DOI:10.5194/adgeo-27-79-2010.

Bärlund I (ed). 2010. *Report on quantification of PEP outcomes. SCENES Deliverables 1.6*. CESR, University of Kassel: Kassel, Germany. Available at www.environment.fi/syke/scenes.

Biggs, HC, Rogers, KH. 2003. An Adaptive System to Link Science, Monitoring, and Management in Practice. In *The Kruger Experience. Ecology and Management of Savanna Heterogeneity,* du Toit JT, Rogers KH, Biggs HC (eds). Island Press: Washington, DC; 59–58.

Biggs BJF, Nikora V, Snelder T. 2005. Linking scales of flow variability to lotic ecosystem structure and function. *River Research and Applications* **21**: 283–298.

Bragg OM, Black AR, Duck RW, Rowan JS. 2005. Approaching the physical-biological interface in rivers: a review of methods for ecological evaluation of flow regimes. *Progress in Physical Geography* **29**(4): 506–531.

Bunn E, Arthington AH. 2002. Basic Principles and Ecological Consequences of Altered Flow Regimes for Aquatic Biodiversity. *Environmental Management* **30**(4): 492–507. DOI: 10.1007/s00267-002-2737-0.

Caissie D. 2006. The thermal regime of rivers: a review. *Freshwater Biology* **51**(8): 1389-1406.

Clarke SJ. 2009. Adapting to climate change: implications for freshwater biodiversity and management in the UK. *Freshwater Reviews* **2**: 51-64. DOI: 10.1608/FRJ-2.1.3.

Döll P, Flörke M. 2005: *Global-Scale Estimation of Diffuse Groundwater Recharge. Frankfurt Hydrology Paper 03*. Institute of Physical Geography, Frankfurt University: Frankfurt am Main, Germany.

Döll P, Siebert S. 2002. Global Modeling of Irrigation Water Requirements. *Water Resources Research* **38**(4): 8.1-8.10.

Döll P, Zhang J. 2010. Impact of climate change on freshwater ecosystems: a global-scale analysis of ecologically relevant river flow alterations. *Hydrology and Earth System Sciences* **14**: 783–799.

Döll P, Kaspar F, Lehner B. 2003. A global hydrological model for deriving water availability indicators: model tuning and validation. *Journal of Hydrology* **270**: 105–134.

Duel H, Meijer K (eds). 2011. *Socio-economic and environmental impacts of future changes in Europe's freshwater resources. SCENES Deliverable 4.6: main report*. Deltares: Delft, the Netherlands. Available at www.environment.fi/syke/scenes.

Dyson M, Bergkamp G, Scanlon J (eds). 2003. *Flow: essentials of environmental flows*. IUCN: Gland, Switzerland and Cambridge, UK.

European Commission. 2000. Directive 2000/60/EC, Establishing a framework for Community action in the field of water policy. *Official Journal of the European Communities* **L327**: 1-72.

Flörke M, Alcamo J. 2004. *European Outlook on Water Use, Final Report, EEA/RNC/03/007.* Center for Environmental Systems Research: Kassel, Germany. Available at scenarios.ew.eea.europa.eu/reports/fol949029/fol040583/Water_stress_final_report.pdf.

Flörke, M, Teichert, E, Bärlund, I. 2011. Future changes of freshwater needs in European power plants. *Management of Environmental Quality: An International Journal* **22**(1): 89–104. DOI:10.1108/14777831111098507.

Graham CT, Harrod C. 2009. Implications of climate change for the fishes of the British Isles. *Journal of Fish Biology* **74**:1143–1205. DOI:10.1111/j.1095-8649.2009.02180.x.

Grantham TE, Merenlender AM, Resh VH. 2010. Climatic influences and anthropogenic stressors: an integrated framework for streamflow management in Mediterranean-climate California, U.S.A. *Freshwater Biology* **55**(Suppl. 1):188–204. DOI:10.1111/j.1365-2427.2009.02379.x.

Hanasaki N, Kanae S, Oki T. 2006. A reservoir operation scheme for global river routing models. *Journal of Hydrology* **327**: 22–41.

Hart DD, Calhoun AJK. 2010. Rethinking the role of ecological research in the sustainable management of freshwater ecosystems. *Freshwater Biology* **55**(Suppl. 1):258–269. DOI:10.1111/j.1365-2427.2009.02370.x.

Heino J, Virkkala R, Toivonen H. 2009. Climate change and freshwater biodiversity: detected patterns, future trends and adaptations in northern regions. *Biological Reviews* **84**:39–54. DOI:10.1111/j.1469-185X.2008.00060.x.

Holling CS. 1973. Resilience and Stability of Ecological Systems. *Annual Review of Ecology and Systematics* **4**:1-23.

IPCC. 2007. Summary for Policymakers. In *Climate Change. The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* Solomon S, Qin D, Manning M, Chen Z, Marquis M., Averyt KB, Tignor M, Miller HL (eds). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Johnson AC, Acreman MC, Dunbar MJ, Feist SW, Giacomello AM, Gozlan RE, Hinsley SA, Ibbotson AT, Jarvie HP, Jones JI, Longshaw M, Maberly SC, Marsh TJ, Neal C, Newman JR, Nunn MA, Pickup RW, Reynard NS, Sullivan CA, Sumpter JP, Williams RJ. 2009. The

British river of the future: How climate change and human activity might affect two contrasting river ecosystems in England. *Science of the Total Environment* **407**:4787–4798. DOI:10.1016/j.scitotenv.2009.05.018.

Junk WJ, Bayley PB, Sparks RE. 1989. The flood pulse concept in river-floodplain systems. *Canadian Journal of Fisheries and Aquatic Sciences* **106**: 110–127.

Kendall MG. 1938. A New Measure of Rank Correlation. *Biometrika* **30**(1/2): 81–93.

Kennen JG, Henriksen JA, Nieswand S. 2007. *Development of the hydroecological integrity assessment process for determining environmental flows for New Jersey streams. US Geological Survey Scientific Investigations Report 2007-5206*. http://pubs.er.usgs.gov/usgspubs/sir/sir20075206.

Kok, K, van Vliet, M. 2011. Using a participatory scenario development toolbox: Added values and impact on quality of scenarios. *Journal of Water and Climate Change* **2**(2–3): 87–105.

Kok K, van Vliet, M, Bärlund I, Dubel A, Sendzimir J. 2011. Combining participative backcasting and exploratory scenario development: Experiences from the SCENES project. Technological Forecasting & Social Change **78**: 835–851. DOI:10.1016/j.techfore.2011.01.004.

Kok K, van Vliet M, Bärlund I, Sendzimir J, Dubel A. 2010. *Pan-European backcasting exercise, enriched with regional perspective, and including a list of short-term policy options. SCENES Deliverable 2.10.* Wageningen University: Wageningen, the Netherlands. Available at www.environment.fi/syke/scenes.

Kundzewicz ZW, Mata LJ, Arnell NW, Döll P, Jimenez B, Miller K, Oki T, Şen Z, Shiklomanov I. 2008: The implications of projected climate change for freshwater resources and their management. Hydrological Sciences Journal **53**(1): 3–10. DOI:10.1623/hysj.53.1.3.

Laize CLR, Hannah DM. 2010. Modification of climate–river flow associations by basin properties. *Journal of Hydrology.* **389**:186–204. DOI:10.1016/j.jhydrol.2010.05.048.

Lytle DA, Poff NL. 2004. Adaptation to natural flow regimes. *TRENDS in Ecology and Evolution* **19**(2): 94–100. DOI: 10.1016/j.tree.2003.10.002.

Millennium Ecosystem Assessment. 2005. *Ecosystems and Human Well-being: Synthesis*. Island Press: Washington, DC.

Monk WA, Wood PJ, Hannah DM, Wilson DA. 2007. Selection of river flow indices for the assessment of hydroecological change. *River Research and Applications* **23**: 113–122.

Monk WA, Wood PJ, Hannah DM. 2008a. Examining the Influence of Flow Regime Variability on Instream Ecology. In *Hydroecology and Ecohydrology: Past, Present and Future*, Wood PJ, Hannah DM, Sadler JP (eds). John Wiley & Sons, Ltd.

Monk WA, Wood PJ, Hannah DM, Wilson DA. 2008b. Macroinvertebrate community response to inter-annual and regional river flow regime dynamics. *River Research and Applications* **24**: 988–1001. DOI: 10.1002/rra.1120.

Moss B. 2010. *Ecology of freshwaters - a view for the twenty-first century*. Wiley-Blackwell: Chichester

Nestler JM, Theiling CH, Lubinski KS, Smith DL. 2010. Reference condition approach to restoration planning. *River Research and Applications* 26: 1199–1219. DOI: 10.1002/rra.1330.

Nilsson C, Reidy C, Dynesius M, Revenga C. 2005. Fragmentation and flow regulation of the world's large river systems. *Science* **308**: 405–408.

Norris RH, Thoms MC. 1999. What is river health? *Freshwater Biology* **41**: 197–209.

Okruszko T, Duel H, Acreman M, Grygoruk M, Flörke M, Schneider C. 2011. Broad-scale ecosystem services of European wetlands—overview of the current situation and future perspectives under different climate and water management scenarios. *Hydrological Sciences Journal* **56**(8): 1501–1517.

Olden JD, Poff NL. 2003. Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. *River Research and Applications* **19**(2): 101-121.

Overton IC, Doody TM. 2012. The Murray-Darling Basin: Ecosystem Response and Adaptation to Drought and Climate Change. In *Drought in Arid and Semi-Arid Environments: A Multi-Disciplinary and Cross-Country Perspective,* Schwabe K, Connor J, Hassan R, Albiac J, Meza-Gonzalez L (eds). Springer, Riverside, USA.

Palmer M, Bernhardt E, Allan JD, Lake P, Alexander G, Brooks S, Carr J, Clayton S, Dahm CN, Follstad Shah J, Galat DL, Loss SG, Goodwin P, Hart D, Hassett B, Jenkinson R, Kondolf G, Lave R, Meyer J, O'donnell T, Pagano L, Sudduth E. 2005. Standards for ecologically successful river restoration. *Journal of Applied Ecology* **42**: 208–217. DOI: 10.1111/j.1365-2664.2005.01004.x.

Piniewski M, Laize CLR, Acreman MC, Okruszko T, Schneider C. 2012 Effect of climate change on environmental flow indicators in the Narew Basin, Poland. *Journal of Environmental Quality*. DOI: 10.2135/jeq2011.0386.

Poff NL, Zimmerman JKH. 2010. Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. *Freshwater Biology* **55**: 194–205.

Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE, Stromberg JC. 1997. The natural flow regime. *Bioscience* **47**: 769–784.

Poff NL, Richter BD, Arthington AH, Bunn SE, Naiman RJ, Kendy E, Acreman MC, Apse C, Bledsoe BP, Freeman MC, Henriksen J, Jacobson RB, Kennen JG, Merritt DM, O'Keeffe JH, Olden JD, Rogers K, Tharme RE, Warner A. 2010. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. *Freshwater Biology* **55**: 147–170. DOI:10.1111/j.1365-2427.2009.02204x.

Richter BD, Baumgartner JV, Powell J, Braun DP. 1996. A Method for Assessing Hydrologic Alteration within Ecosystems. *Conservation Biology* **10**(4): 1163–1174.

Richter BD, Baumgartner JV, Wigington R, Braun DP. 1997. How much water does a river need? *Freshwater Biology* **37**(1): 231–249.

Richter B, Baumgartner JV, Braun DP, Powell J. 1998. A spatial assessment of hydrologic alteration within a river network. *Regulated Rivers: Research & Management* **14**: 329–340.

Richter BD, Warner AT, Meyer JL, Lutz K. 2006. A collaborative and adaptive process for developing environmental flow recommendations. *River Research and Applications* **22**: 297–318.

Robson BJ, Mitchell, BD. 2010. Metastability in a river subject to multiple disturbances may constrain restoration options. *Marine and Freshwater Research* **61:** 778–785.

Rosenfeld JS, Post J, Robins G, Hatfield T. 2007. Hydraulic geometry as a physical template for the River Continuum: application to optimal flows and longitudinal trends in salmonid habitat. *Canadian Journal of Fisheries and Aquatic Sciences* **64**: 755–767. DOI: 10.1139/F07.020.

Schinegger R, Trautwein C, Melcher A, Schmutz S. 2011. Multiple human pressures and their spatial patterns in European running waters. *Water and Environment Journal*. DOI:10.1111/j.1747-6593.2011.00285.x.

Schneider C, Flörke M, Geerling G, Duel H, Grygorukc M, Okruszko T. 2011a. The future of European floodplain wetlands under a changing climate. *Journal of Water and Climate Change* **2**(2–3): 106–122.

Schneider C, Flörke M, Eisner S, Voss F. 2011b. Large scale modelling of bankfull flow: An example for Europe. *Journal of Hydrology* **408**: 235–245.

Souchon Y, Sabaton C, Deibel R, Reiser D, Kershner J, Gard M, Katopodis C, Leonard P, Poff NL, Miller WJ, Lamb BL. 2008. Detecting biological responses to flow management: missed opportunities; future directions. *River Research and Applications* **24**: 506–518. DOI: 10.1002/rra.1134.

Stoddard JL, Larsen DP, Hawkins CP, Johnson RK, Norris RH. 2006. Setting expectations for the ecological condition of streams: the concept of reference condition. *Ecological Applications* **16**: 1267–1276.

Vannote RL, Wayne Minshall G, Cummins KW, Sedell JR, Cushing CE. 1980. The River Continuum Concept. *Canadian Journal of Fisheries and Aquatic Sciences* **37**: 130–137.

Vörösmarty CJ, McIntyre PB, Gessner MO, Dudgeon D, Prusevich A, Green P, Glidden S, Bunn SE, Sullivan CA, Reidy Liermann C, Davies PM. 2010. Global threats to human water security and river biodiversity. *Nature* **467**: 555–561. DOI: 10.1038/nature09440.

Webb BW, Hannah DM, Moore RD, Brown LE, Nobilis F. 2008. Recent advances in stream and river temperature research. *Hydrological Processes* **22**: 902–918. DOI: 10.1002/hyp.6994.

Wilby RL, Orr H, Watts G, Battarbee RW, Berry PM, Chadd R, Dugdale SJ, Dunbar MJ, Elliott JA, Extence C, Hannah DM, Holmes N, Johnson AC, Knights B, Milner NJ, Ormerod SJ, Solomon D, Timlett R, Whitehead PJ, Wood PJ. Evidence needed to manage freshwater ecosystems in a changing climate: Turning adaptation principles into practice. *Science of The Total Environment* **408**(19):4150–4164. DOI: 10.1016/j.scitotenv.2010.05.014.

Wright JF, Clarke RT, Gunn RJM, Kneebone NT, Davy-Bowker J. 2004. Impact of major changes in flow regime on the macroinvertebrate assemblages of four chalk stream sites, 1997–2001. *River Research and Applications* **20**(7): 775-794. DOI: 10.1002/rra.790.

Xenopoulos MA, Lodge DM, Alcamo J, Märker M, Schulze K, Van Vuuren DP. 2005. Scenarios of freshwater fish extinctions from climate change and water withdrawal. *Global Change Biology* **11**: 1557–1564. DOI: 10.1111/j.1365-2486.2005.01008.x.

Table 1 Variables for the Indicators of Hydrological Alteration (adapted from Richter et al., 1996)

IHA variables	*IHA group*	*Regime characteristics*
Mean value for each calendar month (x12)	1	Magnitude; Timing
Annual minima 1-, 3-, 7-, 30-, and 90-day means (x5) Annual maxima 1-, 3-, 7-, 30-, and 90-day means (x5)	2	Magnitude; Duration
Julian dates of 1-day minimum and maximum (x2)	3	Timing
Numbers of high pulses[a] and low pulses[b] (x2) Mean durations of high and low pulses (x2)	4	Magnitude; Frequency; Duration
Numbers of flow rises and flow falls (x2) Mean rise and fall rates (x2)	5	Frequency; Rate of change

[a] number of times flow rises above 75th flow percentile
[b] number of times flow drops below 25th flow percentile

Table 2 Monthly Flow Regime Indicators (MFRI)

MFRI variables (one value per year)	*MFRI[c] (one value per record)*	*Flow type*	*Regime characteristics*	*Analogue IHA variables*
Number of months above threshold[a]	Median (1) IQR[d] (2)	High flows	Magnitude; Frequency	Number of high pulses
Month of maximum flow (1-12)	Mode (3)	High flows	Timing	Julian date of 1-day maximum
January mean flow	Median (4) IQR (5)	Seasonal flows	Magnitude; Timing	January mean flow
April mean flow	Median (6) IQR (7)	Seasonal flows	Magnitude; Timing	April mean flow
July mean flow	Median (8) IQR (9)	Seasonal flows	Magnitude; Timing	July mean flow
October mean flow	Median (10) IQR (11)	Seasonal flows	Magnitude; Timing	October mean flow
Number of months below threshold[b]	Median (12) IQR (13)	Low flows	Magnitude; Frequency	Number of low pulses
Month of minimum flow (1-12)	Mode (14)	Low flows	Timing	Julian date of 1-day minimum
Number of sequences at least two-month long below threshold[b]	Median (15) IQR (16)	Low flows	Magnitude; Frequency; Duration	n/a

[a]Threshold = all-data naturalised Q5 from 1961-1990 (95th percentile)
[b]Threshold = all-data naturalised Q95 from 1961-1990 (5th percentile)
[c]Indicator identification number between parentheses
[d]IQR: Inter-Quartile Range

Table 3 Distribution of ERFA classes per runs (% of cells)

		None	Low	Medium	High
IPCM4	*Natural*	5	25	54	16
	EcF	5	18	54	22
	FoE	5	19	55	21
	PoR	5	20	55	20
	SuE	5	20	55	20
MIMR	*Natural*	5	26	55	14
	EcF	5	24	54	17
	FoE	5	24	55	16
	PoR	5	25	55	15
	SuE	5	25	55	15

Table 4 Summary matrix of differences in ERFA classes between all runs (% of different cells)

		IPCM4					MIMR				
		Natural	*EcF*	*FoE*	*PoR*	*SuE*	*Natural*	*EcF*	*FoE*	*PoR*	*SuE*
IPCM4	*Natural*		21	20	18	17	36	37	37	37	37
	EcF			5	7	8	37	34	35	37	37
	FoE				4	6	36	34	34	36	36
	PoR					4	35	33	34	35	35
	SuE						35	33	33	35	35
MIMR	*Natural*	36	37	36	35	35		9	8	5	3
	EcF	37	34	34	33	33			5	7	8
	FoE	37	35	34	34	33				5	6
	PoR	37	37	36	35	35					4
	SuE	37	37	36	35	35					

Figure captions

Figure 1 Study geographical extent (grey outlines); WaterGAP cells used for method testing (black dots)

Figure 2 Methodological flow chart

Figure 3 Box plot of the percentages of cells (out of ~33,368) for which indicators are different from the baseline across all ten model runs (indicator identification numbers as in Table 2)

Figure 4 Geographical location of ERFA classes for Natural IPCM4 2050s model run: future naturalised flows, i.e. climate model A2-IPCM4 only, no water usage, no socio-economic scenario, 2040-2069 projection period; blue, no risk; green, low risk; amber, medium risk; red, high risk

Figure 5 Geographical location of ERFA classes for Natural MIMR 2050s model run: future naturalised flows, i.e. climate model A2-MIMR only, no water usage, no socio-economic scenario, 2040-2069 projection period; blue, no risk; green, low risk; amber, medium risk; red, high risk

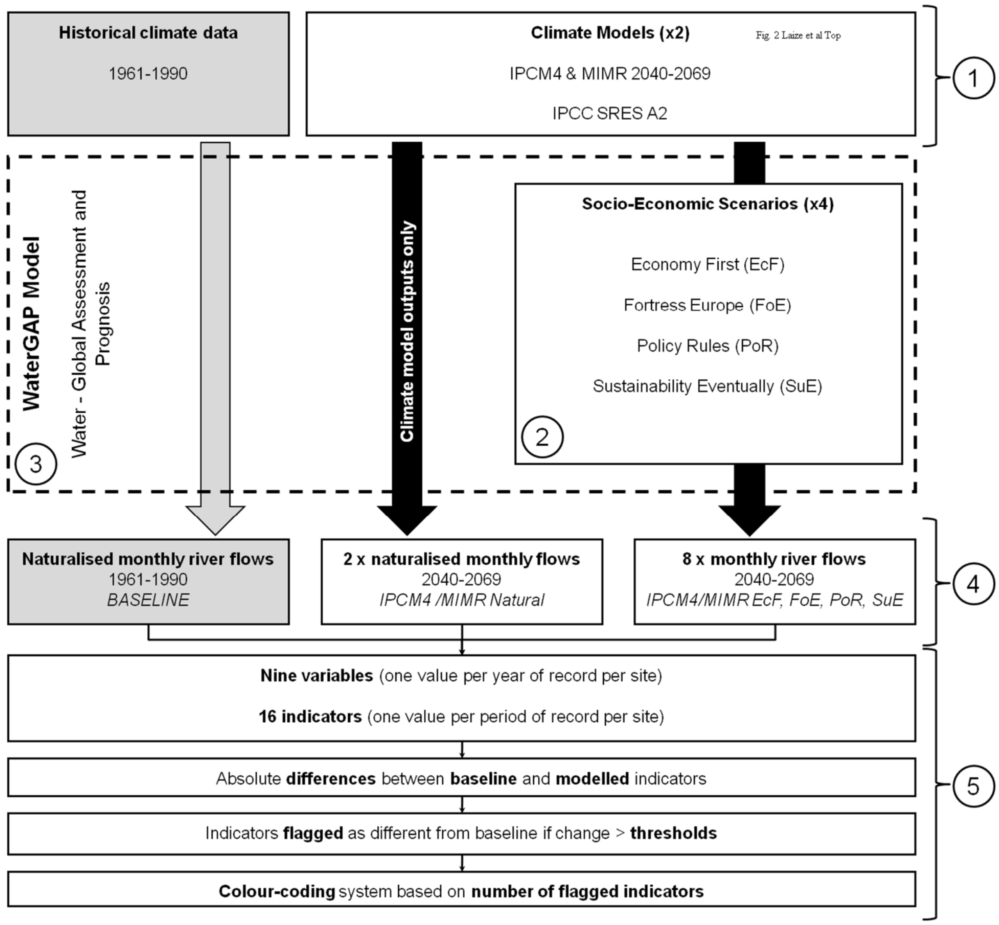
Figure 6 Geographical location of ERFA classes for the eight model runs including the four socio-economic scenarios (top to bottom): Economy First (EcF), Fortress Europe (FoE), Policy Rules (PoR), Sustainability Eventually (SuE); climate models, A2-IPCM4 (left), A2-MIMR (right); 2040-2069 projection period; blue, no risk; green, low risk; amber, medium risk; red, high risk

Figure 7 2050s ERFA geographical location changes between IPCM4 Natural and MIMR Natural: green, same ERFA; blue, MIMR less severe than IPCM4; red, MIMR more severe

Figure 8 2050s ERFA geographical location changes between Natural and socio-economic scenarios(top to bottom): Economy First (EcF), Fortress Europe (FoE), Policy Rules (PoR), Sustainability Eventually (SuE); climate models A2-IPCM4 (left), A2-MIMR (right); green, same ERFA; red, different ERFA

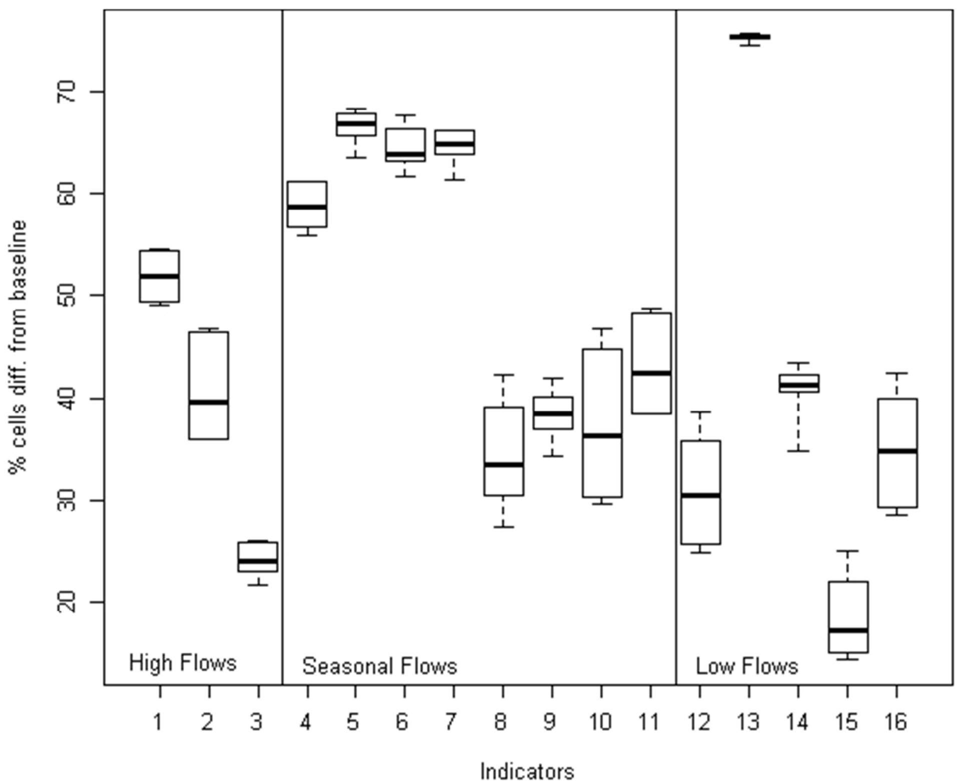
Figure 9 Summary of ERFA classes across all 10 model runs: categories ‘None’, ‘Low’, ‘Medium’, ‘High’ for cells with a single ERFA class for all 10 runs; categories ‘None/Low’, ‘Low/Medium’, ‘Medium/High’ for cells with either of the two ERFA classes for all 10 runs; category ‘Mixed’ for cells that are inconsistently classified

Study geographical extent (grey outlines); WaterGAP cells used for method testing (black dots)
1980x1400mm (96 x 96 DPI)

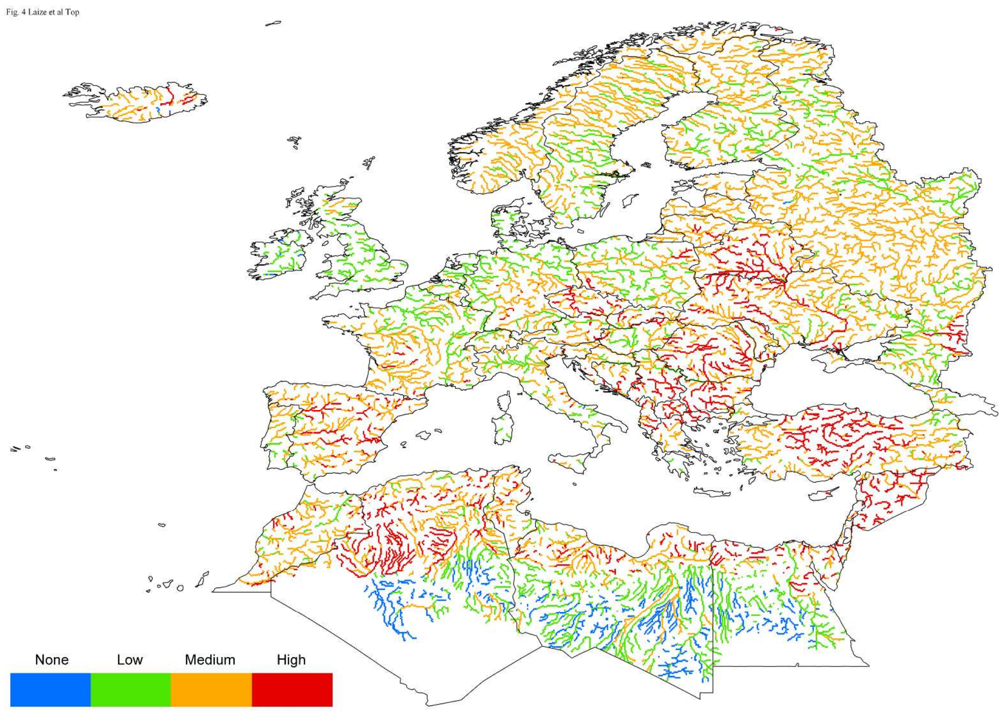


Methodological flow chart
401x372mm (96 x 96 DPI)

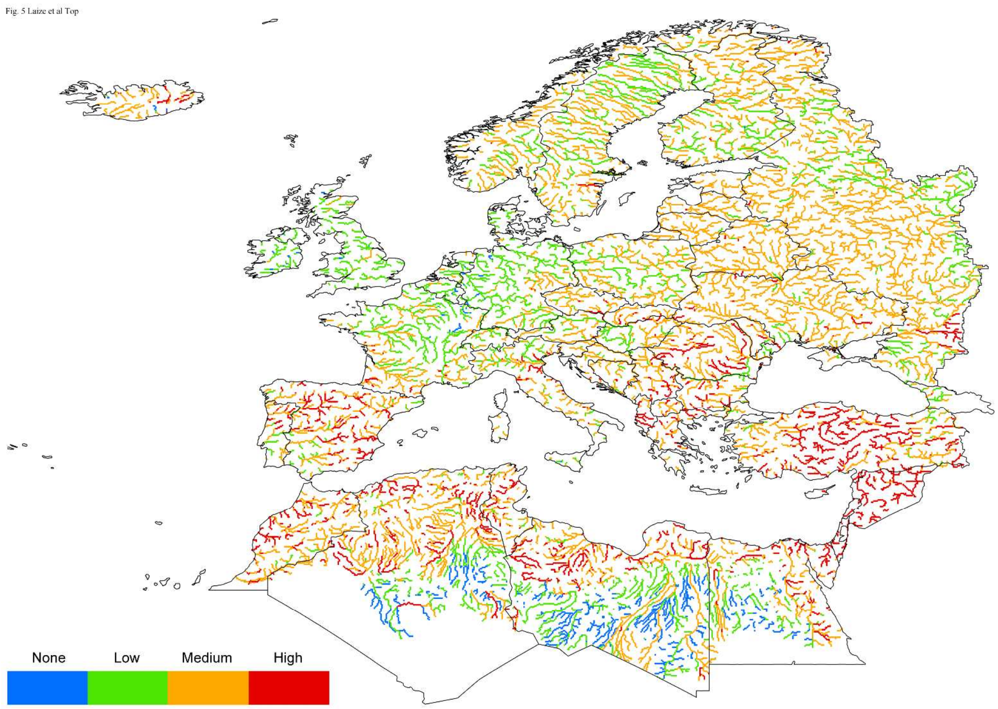
Fig. 3 Laize et al Top



Box plot of the percentages of cells (out of ~33,368) for which indicators are different from the baseline across all ten model runs (indicator identification numbers as in Table 2)
156x140mm (96 x 96 DPI)

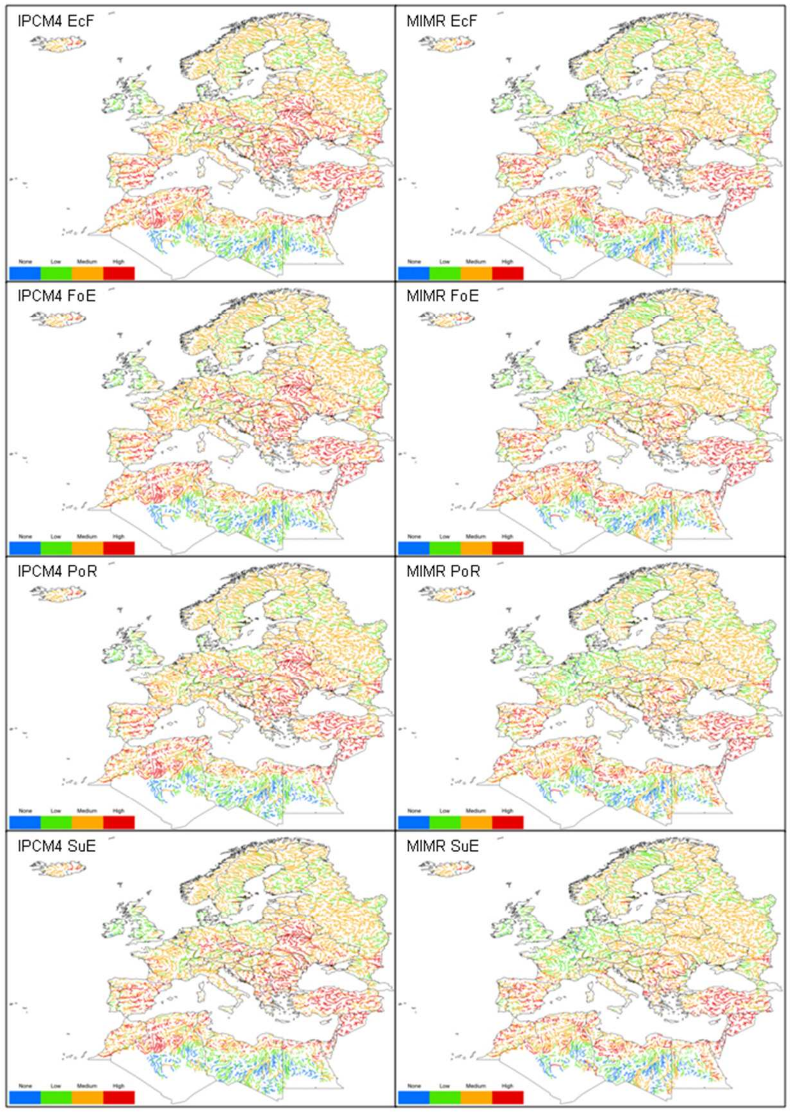


Geographical location of ERFA classes for Natural IPCM4 2050s model run: future naturalised flows, i.e. climate model A2-IPCM4 only, no water usage, no socio-economic scenario, 2040-2069 projection period; blue, no risk; green, low risk; amber, medium risk; red, high risk
1980x1400mm (96 x 96 DPI)



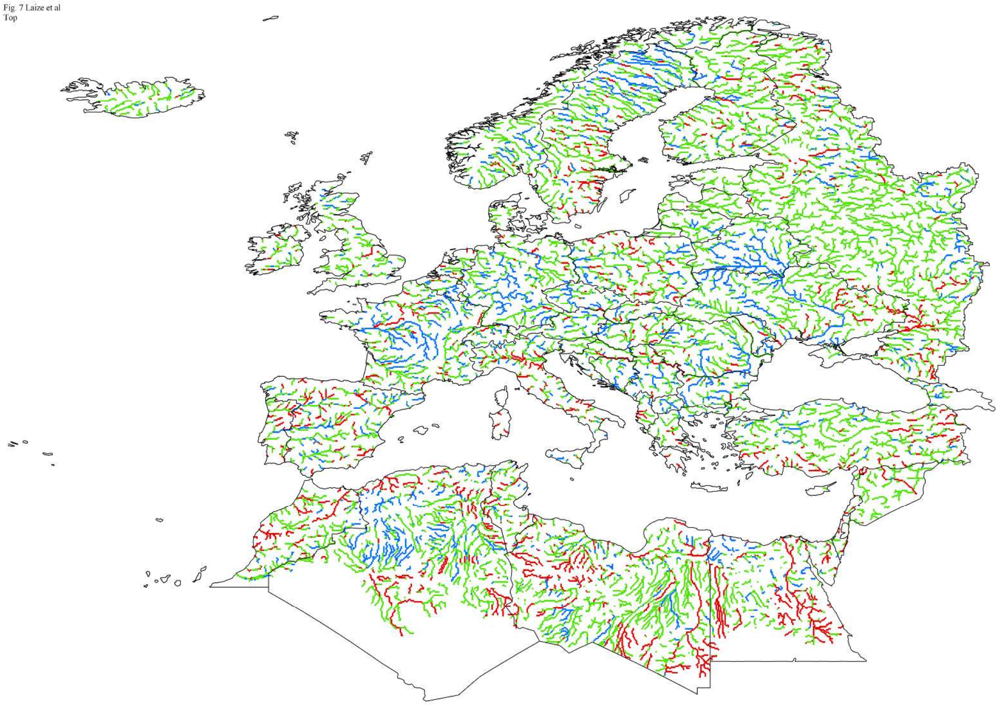
Geographical location of ERFA classes for Natural MIMR 2050s model run: future naturalised flows, i.e. climate model A2-MIMR only, no water usage, no socio-economic scenario, 2040-2069 projection period; blue, no risk; green, low risk; amber, medium risk; red, high risk
1980x1400mm (96 x 96 DPI)

Fig. 6 Laize et al Top



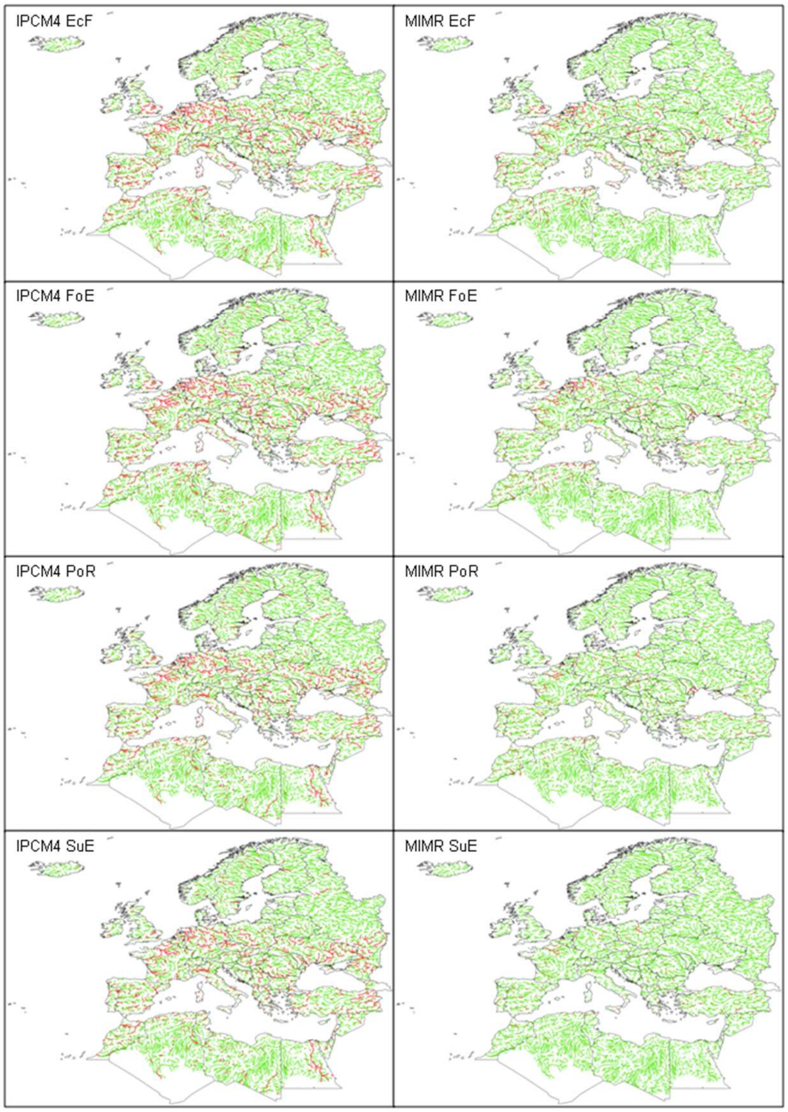
Geographical location of ERFA classes for the eight model runs including the four socio-economic scenarios (top to bottom): Economy First (EcF), Fortress Europe (FoE), Policy Rules (PoR), Sustainability Eventually (SuE); climate models, A2-IPCM4 (left), A2-MIMR (right); 2040-2069 projection period; blue, no risk; green, low risk; amber, medium risk; red, high risk
190x275mm (96 x 96 DPI)

Fig. 7 Laize et al
Top

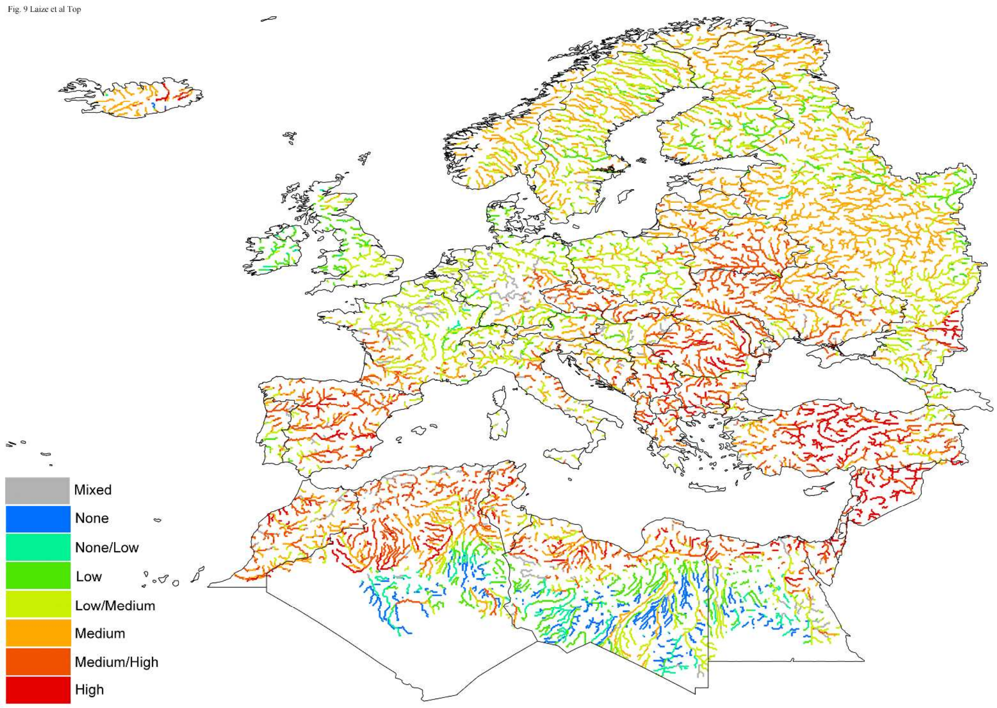


2050s ERFA geographical location changes between IPCM4 Natural and MIMR Natural: green, same ERFA; blue, MIMR less severe than IPCM4; red, MIMR more severe
1980x1400mm (96 x 96 DPI)

Fig. 8 laize et al Top



2050s ERFA geographical location changes between Natural and socio-economic scenarios(top to bottom): Economy First (EcF), Fortress Europe (FoE), Policy Rules (PoR), Sustainability Eventually (SuE); climate models A2-IPCM4 (left), A2-MIMR (right); green, same ERFA; red, different ERFA
190x275mm (96 x 96 DPI)



Summary of ERFA classes across all 10 model runs: categories ‘None’, ‘Low’, ‘Medium’, ‘High’ for cells with a single ERFA class for all 10 runs; categories ‘None/Low’, ‘Low/Medium’, ‘Medium/High’ for cells with either of the two ERFA classes for all 10 runs; category ‘Mixed’ for cells that are inconsistently classified
1980x1400mm (96 x 96 DPI)