Accounting for environmental flow requirements in global water assessments

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Abstract

With growing water needs for food production and other human needs, it is necessary to improve the quantification of “Environmental Flow Requirements (EFRs)” in order to quantify the amount of water needed to sustain freshwater ecosystems. In this study, five methods for calculating EFRs were compared with 11 case studies of locally-assessed EFRs. We used three existing methods (Smakhtin, Tennant and Tessmann) and two newly developed methods (the Variable Monthly Flow method (VMF) and the Q_{90}_Q_{50} method). All methods were compared globally and validated at local scales while mimicking the natural flow regime. The VMF and the Tessmann methods use algorithms to classify flow regime into high, intermediate and low-flow months to take into account intra-annual variability by allocating EFRs with a percentage of mean monthly flow (MMF). The Q_{90}_Q_{50} method allocates annual flow quantiles (Q_{50} and Q_{90}) depending on the flow season. The results showed that, on average, 37% of annual discharge was required for sustaining environment flows. More water is needed for environmental flows during low-flow periods (46% to 71% of average low-flows) compared to high-flow periods (17% to 45% of average high-flows). Environmental flow requirements (EFRs) estimates from Tennant, Q_{90}_Q_{50} and Smakhtin methods were above the locally-calculated EFRs for river systems with relatively stable flows and were lower than the locally-calculated EFRs for rivers with variable flows. VMF and Tessmann methods showed the highest correlation with the locally-calculated EFRs (R^2=0.91). The main difference between the Tessmann and VMF methods is that the Tessmann method allocates all water to EFRs in low-flow periods and the VMF method allocates 60% of the flow. Thus, other water sectors such as irrigation can withdraw water up to 40% of the flow during low-flow season while freshwater ecosystems are sustained in reasonable ecological conditions. The global applicability of those five methods was tested by using the global vegetation and hydrological model LPJml. The calculated global annual EFRs for “fair” ecological conditions represent between 25 to 46% of mean annual flow (MAF). Variable flow regimes such as the Nile have lower EFRs (ranging from 12 to 48% of MAF) than stable tropical regimes such as the Amazon (EFRs ranging from 30 to 67% of MAF).

1 Introduction

One of the main challenges of the 21st century is to manage water and other natural resources so that human needs can be satisfied without harming the environment. By 2050, agricultural production is projected to increase by 70 % compared to 2000 in order to secure sufficient food production for 9 billion people (Alexandratos and Bruinsma, 2012). This increase in future food production will result in an increase in water demand (Biemans et al., 2011). As a result about 60% of the world population could face surface water shortages from lakes, rivers and reservoirs (Rockström et al. (2009).

Today, 65 % of global rivers are considered under moderate to high threat in terms of human water security and biodiversity (Vorosmarty et al., 2010). Since the beginning of the 20th century, more than 800 000 dams have been developed to facilitate increased withdrawals and currently 75% of the main rivers are fragmented (Biemans et al., 2011;Richter et al., 2003). Some large river basins, like the Yellow river have even seen their flow reduced by almost 75% in 30 years due to increasing water withdrawals (Changming and Shifeng, 2002). Also in many rivers flows are inadequate to sustain the deltas. This is the case in for example the Colorado or the Nile (Gleick, 2003). In other river basins with high biodiversity index such as the Amazon or Mekong river, flow deviation and dams construction are planned at the possible expense of fish biomass and biodiversity (Ziv et al., 2012).

River flow is the main driver to maintain a river in a good ecological state (Poff et al., 2009). Human activities have impaired freshwater ecosystems due to flow alteration by water withdrawal, river pollution, land use change (including deforestation) and overfishing (Dudgeon, 2000). Stressors associated with the reduction in flow and in water quality are the most obvious causes of biodiversity hazard by directly degrading aquatic ecosystems (Vorosmarty et al., 2010;O'Keeffe, 2009;Pettit et al., 2001;Doupé and Pettit, 2002). Between 1970 and 2000, freshwater ecosystem species have declined by 36% (Loh et al., 2010). With increasing future water demand for agriculture, industry and human consumption, freshwater ecosystems will therefore be under great pressure in the coming decades. In addition, climate change is expected to affect river discharge and its ecosystem with a prediction of decreased low-flows and rising river temperatures (Vliet et al., 2013).

Over the last ten years, global water assessments (GWAs) have evaluated water resources and water scarcity using global hydrological models (GHMs) (Arnell, 2004;Alcamo et al., 2007;Rockström et al., 2009;van Beek et al., 2011;Hoff et al., 2010;Hanasaki et al., 2008). GWAs have highlighted regions with current and future water scarcity. However most of these studies have neglected the water required by the environment also known as environmental flow requirements (EFRs), Only a few studies have attempted to include some aspects of environmental flows (Hoekstra and Mekonnen, 2011;Smakhtin et al., 2004;Hanasaki et al., 2008;Gleeson et al., 2012).

According to the Brisbane Declaration (2007), “environmental flows describe the quantity, quality and timing of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems”. Environmental flows can also be defined as the flows to be maintained in rivers by managing the magnitude, frequency, duration, timing, and rate of change of flow events (O'Keeffe, 2009). Environmental flow (EF) methods should take into account the natural variability of river flow by allocating different flow components in order to maintain and/or restore freshwater ecosystems (Acreman et al., 2008) and riparian vegetation (Bunn and Arthington, 2002;O'Keeffe and Quesne, 2009;Kingsford and Auld, 2005;Pettit et al., 2001;Bejarano et al., 2011). For example, sustaining a minimal flow is usually important to guarantee that aquatic species stay alive, while flood flows are usually crucial for sediments recruitments and for the maintenance of wetlands and floodplains (Hugues and Rood, 2003;Bunn and Arthington, 2002;Acreman et al., 2008;Bigas, 2012). Disrupting a stable flow regime can also impair aquatic ecosystems and favour proliferation of invasive species and more generalist fish species (O'Keeffe, 2009;Marchetti and Moyle, 2001;Poff et al., 2009).

There has been important efforts to define EFRs based on eco-hydrological relationships in individual rivers (Richter et al., 2006) but there has been limited upscaling of individual methods to global or regional scales. In general, eco-hydrological relationships are far from being linear at local scales. Therefore, defining eco-hydrological relationships at global scale is even more challenging. Some recent studies showed efforts in relating global eco-hydrological responses to flow alteration (Xenopoulos et al., 2005;Iwasaki et al., 2012;Yoshikawa et al., 2013) thanks to the development of a world database on fish biodiversity (Oberdorff et al., 2011). However, it remains difficult to relate freshwater biodiversity with flow metrics at both local and global scale (Poff and Zimmerman, 2010). In the current global water assessments EFRs are almost always neglected or included in a very simplified way. By ignoring EFRs, the quantity of water available for human consumption globally is probably overestimated (Gerten et al., 2013). To be able to assess where enough water will be available for increasing agricultural production in a sustainable way, it is necessary to set limits to water withdrawals in time and space by fully acknowledging nature as a water user.

The aim of this study is to compare different EF methods and their applicability in GHMs to set limit to water withdrawals. In this paper, we first present an overview of existing EF methods. Secondly, we present the selection and development of 5 hydrological EF methods that were compared with EFRs calculated in 11 case studies. In a final step we present a comparison of the 5 hydrological EF methods applied to a global hydrological and vegetation model LPJml (Bondeau et al., 2007;Gerten et al., 2004).

2 Review of Environmental flow methods

Currently, more than 200 environmental flow methods exist (Tharme, 2003). EF methods are classified into four types: hydrological methods, hydraulic rating methods, habitat simulation methods, and holistic methods (Table 1). Most of the EF methods were developed at river or basin scale in the context of flow restoration projects (Richter et al., 2006) or for assessing the ecological status of rivers at a regional, national or continental level such as the Water Framework Directive 2000/60/EC (Council, 2000). Global EF methods are mainly based on hydrological methods due to a lack of global ecohydrological data (Richter et al., 2006;Poff and Zimmerman, 2010).

2.1 Hydrological methods

Hydrological methods are usually based on annual minimum flow thresholds such as *7Q10*, the lowest flow that occurs for seven consecutive days once in ten years (Telis and District, 1992) or Q_{90}, the flow exceeded 90% of the period of record (NGPRP, 1974). The desired level of ecological conditions of a river is often determined in a first step such as in the Tennant method (Tennant, 1976) where seven classes going from ‘severe degradation’ (F) to ‘outstanding’ ecological conditions (A) were defined. According to this classification, a different percentage of the annual flow is allocated during high-flow and low-flow seasons. The Tessmann method (1980) considers intra-annual variability by allocating percentages of monthly flow to calculate EFRs depending on the different flow seasons (high, intermediate or low-flow months). Richter et al. (1997) divided the Indicators of Hydrological Alteration (IHA) into five groups: magnitude, timing, duration, frequency and rate of change and determined some environmental flow components (EFCs) such as the maintenance flow during dry and normal years (Mathews and Richter, 2007). Alternatively, EFRs can be calculated with a method called the “Range of Variability Approach (RVA)” which calculates EFRs as a range comprised between the 25th and 75th monthly flow percentile in non-parametric analyses (Armstrong et al., 1999;Babel et al., 2012) or as a range of mean monthly flow (±standard deviation) in parametric analyses (Smakhtin et al., 2006;Richter et al., 2012). The advantage of hydrological methods is that they are simple and fast EF methods to use in preliminary assessments or when ecological datasets are not available. They can easily be implemented at local and global scale depending on their level of complexity and the availability of hydrological data.

2.2 Hydraulic methods

Hydraulics methods are used at a local scale when river cross-sections measurements are available. They can eventually complement habitat simulation models for calculating the area necessary for fish habitat survival (Gippel and Stewardson, 1998;Espegren, 1998). The inconvenience of this method is that it requires river hydraulic measurements and is specific to each river section.

2.3 Habitat simulation methods

Habitat simulation models make use of ecohydrological relationships. They are based on correlations between hydraulic parameters such as flow velocity and certain species of freshwater ecosystems. For example, the Instream Flow Incremental Methodology (IFIM) requires datasets of river discharge, river temperature and fish species richness (Bovee, 1986;Bovee et al., 1998). The Physical Habitat Simulation Model or PHABSIM (Milhous, 1999) is based on the theory that the quality and quantity of physical habitat is related to the environmental needs of aquatic ecosystems of each life stage (Palau and Alcázar, 2010;Jowett, 1989). The advantage of habitat simulation models is that they take into consideration riverine ecosystems but data collection could be costly and time consuming. Habitat simulation models also need re-calibration when they are applied to a different region and are usually species specific (McManamay et al., 2013).

2.4 Holistic methods

Holistic methods are a combination of hydrological, hydraulic, habitat simulation methods and expert knowledge (Shafroth et al., 2009;Poff et al., 2009). For example, the Building Block Model is a well-documented method to estimate EFRs at local or basin scale (King and Louw, 1998;King and Brown, 2010;Tharme, 2003;Hugues and Rood, 2003). The building block method supports the principle that it is fundamental to maintain certain components of the natural flow. The flow blocks encompass low-flows and high-flows both defined for normal and dry years. The DRM, desktop reserve model (Hughes, 2001) provides estimates of these building blocks for each month of the year. River streams are classified according to their level of flow alteration (from A to D) and the decision on ecological flows will depend on those classes (Kashaigili et al., 2007). The Downstream Response to Imposed Flow Transformations (DRIFT) is a model that uses 10 ecological relevant flow categories such as wet and dry seasonal low-flows, periodicity of floods and flow variability via flow duration curves (Arthington et al., 2003). Finally, the Ecological Limits of Hydrologic Alteration (ELOHA) approach includes both a scientific and a social approach. The method uses a hydrological classification of natural flow regime types and calculates the rate of flow alteration between natural and actual conditions. The second part of the method uses ecohydrological relations to determine EFRs and expert knowledge is included in the last part of the assessment. Holistic methods require large amounts of data and time and are difficult to upscale due to the divergence in freshwater ecosystems, flow regime types, water management techniques and different socio-economic contexts. The strength of holistic methods is that they promote inter-disciplinarity where hydrologists, geo-morphologists, biologists and sociologists methods are used to find the best compromise between water demand for freshwater ecosystems and water requirements for anthropogenic purposes (Poff et al., 2009).

2.5 Global application of environmental flow requirement methods

Smakhtin et al. (2004) developed the first EF method for application within global hydrological models. They defined four possible desired ecological river statuses including: pristine, good, fair and degraded, following the recommendations of the Department of Water Affairs and Forestry (DWAF, 1997). A low-flow component is allocated to each ecological river status such as Q_{50} for good ecological status, Q_{75} for moderate ecological status, Q_{90} for fair conditions and NA for degraded river status. Smakhtin et al. (2004) developed a method assuming a fair ecological state of global rivers and Q_{90} was defined as the base flow requirement. To determine high-flow requirements, the global river discharge was classified according to their baseflow index, which determines the river flow regime. Hanasaki et al. (2008) developed an EF method considering intra-annual variability based on global monthly river flows. They defined four different river regimes: dry, wet, stable and variable. For each class, they determined EFRs as a percentage of mean monthly flow (MMF) depending on the flow regime type (from 10 to 40% of MMF). EFRs are also determined with the ecological status “fair” based on the Tennant method (Hanasaki, personal communication). Hoekstra and Mekonnen (2012) evaluated monthly EFRs by applying the “presumptive environmental flow standard” defined by Richter et al. (2012). They limited water consumption to 20% of total discharge, however, it did not imply that 80% of the total discharge was unavailable but they show in which period of the year net water availability fails in meeting water demand. In another recent global water assessment, EFRs were defined as the monthly flow quantile Q_{90} in the PCR-GLOBWB model (Gleeson et al., 2012). In this study, we selected 5 hydrological EF methods to compare them with 11 locally-calculated EFRs cases with the aim to have a simple and reliable global EF method that takes into account intra-annual variability.

3 Methods

3.1 Criteria for selecting case studies

Eleven case studies were selected according to their types of EF methods, river flow regimes, geo-localizations and Major Habitat Types (MHTs) (Table 1, Fig. 1). Major Habitat Types such as temperate coastal rivers and large river deltas are described in the Freshwater Ecoregions Of the World (FEOW), which classify global rivers into 426 freshwater ecoregions (Abell et al., 2008). We chose this classification because it is more robust than a simple global river classification which is usually based on climate zones and/or river discharge (Haines et al., 1988;McMahon et al., 2007). MHTs classification is based on riverine species biodiversity, endemism and river fragmentation. The description of the geo-localization of the case studies is described in Table 2 and Fig. 1. In our selection of 11 case studies, a prerequisite was that 5 sub-groups of MHTs (xeric, temperate, tropical and polar) should be represented by at least 2 case studies. Five out six continents should be represented by at least 1 or 2 case studies. The type of flow regimes of the different case studies should vary between stable and variable flow regime. Finally the choice of EF method in the case study should use a habitat simulation model or a holistic model because those methods rely on ecological datasets. For example, one of our selected cases (the Silvan River case) uses a habitat simulation model and another selected case (Hong Kong) uses a sample of macro-invertebrates to determine optimum and detrimental EFRs thresholds. In other cases, hydrological EF methods were accepted when ecological datasets were not available (Table 3). For example, in the Tanzanian case study, a hydrological method (the DRM model approach) was used.

3.2 Hydrological datasets

Hydrological datasets of individual case studies were obtained from the Global Runoff Data Centre (available at http: //grdc.bafg.de) or from the authors of the case studies (Table 2). Mean monthly flows were calculated with historical datasets of 8 to 30 years to represent the “natural” or “pristine” ecological conditions of the river. In other cases, such as in the Ipswich River case study and the Hong Kong case study, a 20-year average of simulated natural monthly flow was used (section 3.6).

3.3 Hydrological indexes

The analyses were all computed over a 40-year time period (from 1961 to 2000) in order to take into account inter-annual variability. The flow regime of the selected case studies were analysed using several hydrological indicators and river classification. To compare the case studies, we calculated some hydrological flow indexes such as the base flow index (BFI) and a hydrological variability index (HVI):

$$BFI = \frac{Q90}{MAF} \qquad (1)$$

Where: Q_{90} – the annual flow which is equalled or exceeded for 90% of the period of record, *MAF* – the mean annual flow.

$$HVI = \frac{(Q25 - Q75)}{Q50} \qquad (2)$$

Where: Q_{25} – the annual flow which is equalled or exceeded for 25% of the period of record, Q_{75} – the flow which is equalled or exceeded for 75% of the period of record, Q_{50} – the flow which is equalled or exceeded for 50% of the period of record.

Finally, we classified our case studies with their respective number of high-flow (HF), intermediate-flow (IF) and low-flow (LF) months. HF is defined as MMF ≥ 80% of MAF, IF is defined as MMF ≥ 40% of MAF and MMF < 80% of MAF and LF is defined as MMF < 40% of MAF (Table 3).

3.4 Description of the case studies

The hydrological description of the 11 case studies is shown in Table 3. The first case is the Bill Williams River (BWR), located in Arizona, in the US, it is classified in the xeric freshwater habitat type and is characterized by a long low-flow season (more than 6 months) with a low Base Flow Index (BFI=5.3%). The second case is the Sharh Chai River; it also belongs to the xeric freshwater habitat type. It is characterized by a long period of low-flow (about 6 months) and by a high BFI (21%). Then, four temperate coastal rivers were selected: the Ipswich River in the US, the Silvan River in the North-West of Spain, the upstream flow of the Osborne River in Zimbabwe and the Huasco River in Chile (Table 3; Fig. 1). They all have relatively stable flow regimes with a strong baseflow index (BFI≥20%) and a hydrological variability index (HVI<1). Two case studies were selected in the polar freshwater habitat types: the Voijm River in Sweden and the Newhalen River in Alaska, both rivers are characterized by a strong BFI of 51% and 22% respectively. Finally, three case studies are located in tropical floodplains and coastal habitat types: a stream near Hong Kong in China, the Gna River in Vietnam and the Great Ruaha River in Zimbabwe. They are all characterized by a monsoon season of 3-4 months with a low BFI (between 5 and 15) and the Great Ruaha River is characterised by the strongest variability index (4.3).

3.5 Description of local environmental flow methods

For all case studies, the five global environmental flow methods were compared with the locally-calculated EFRs (Table 3-5, Fig. 2). In five case studies, hydrological methods were used to determine EFRs at local scale. Those methods were developed and validated with statistical analyses of daily flow datasets (e.g. GEFC, Hugues method, Tennant, Desktop reserve model). One case study used a hydraulic method based on the river cross section of the river in order to assess suitable habitat area for fish habitat (R2 cross method). Three case studies used EF methods with eco-hydrological relationships such as PHABSIM and RHYHABSIM. Within the Hong Kong case study an empirical relationship between macroinvertebrates survival and river flow was developed. Finally, one case study used a holistic approach by including expert knowledge (Swedish case).

3.6 Selection of global environmental flow methods

3.6.1 Ecological conditions

At global scale, there is no existing dataset indicating the level of ecological condition of rivers, neither a dataset with the desired ecological status of rivers worldwide. In absence of such a dataset, we defined the global desired ecological conditions of rivers as “fair” as in Smakhtin et al. (2004). We applied a desired “fair” ecological conditions to the 5 selected EF methods at the exception of the Tennant method for which the algorithm on desired “good” ecological conditions algorithm was used to be above the global estimates of EFRs (Smakhtin et al., 2004;Hanasaki et al., 2008). We excluded methods that did not use “fair” ecological conditions such as the method defined by Hoekstra et al. (2012).

3.6.2 Global environmental flow method criteria

In this study, we selected three existing hydrological EF methods and developed two new hydrological EF methods. The selected and developed EF methods should be easily implementable in global hydrological models. The type of algorithm should use mean monthly or annual flow (defined as parametric analyses) or mean annual flow quantile (defined as non-parametric analyses). We excluded EF methods that use daily flows as inputs (e.g. Hanasaki method) because GHMs are mostly validated on a monthly time scale (Döll et al., 2003;Werth and Güntner, 2010;Portmann et al., 2010;Pokhrel et al., 2011;Biemans et al., 2011). The 3 selected existing EF methods were the Tennant, Smakhtin and Tessmann methods. It is essential to define EFRs at shorter timescales than annual timescales to be able to compare EFRs with other water sectors such as irrigation which is planned on sub-daily, daily or monthly time-step. Therefore, the algorithms of the Smakhtin and Tennant methods were adjusted from annual to monthly time-step in order to compare EFRs with monthly irrigation requirements in future water assessments. Therefore, we divided river hydrograph into low/high flow months and define EFRs algorithm for each flow season (high-flow or low-flow months). For example, in the Smakhtin method, low-flow requirements (LFRs) are now allocated during low-flow months and high-flow requirements (HFRs) are now allocated during high-flow months. By including intra-annual variability to our EF methods, we present an improved representation of EFRs compared with EF methods based on annual flows.

3.6.3 Design of new EF methods

Two out of the five EF methods were newly developed for the purpose of this study. One method is based on annual flow quantiles (Q_{90}_Q_{50}) and the other method is based on average monthly flows (the VMF method). We chose to develop a purely non-parametric method (Q_{90}_Q_{50}), which uses flow quantiles to allocate minimum instream flow during the high-flow and low-flow seasons. EFRs are calculated with the allocation of the annual flow quantile (Q_{90}) during the low-flow season and with the allocation of the annual flow quantile (Q_{50}) during the high-flow season based on the study of Allain and El-Jabi (2002), which compared different baseflow indexes for allocating EFRs (Table 3). We also developed a parametric method: the VMF method. This method follows the natural variability of river discharge by defining EFRs on a monthly basis such as Tessmann and Hoekstra method except that the VMF method adjust EFRs according to the flow season. The VMF method was developed to increase the protection of freshwater ecosystems during the low-flow season with a reserve of 60% of the MMF and a minimum flow of 30% of MMF during the high-flow season. The VMF method allows other water users to withdraw water during the low-flow season up to 40% of the MMF. In all the EF methods except the VMF method and the Tessmann methods, low-flow season was determined when the MMF was below mean annual flow (MAF) and high-flow season when MMF was above MAF. In two out five methods, intermediate-flows were determined in order to make a smooth transition between high-flow and low-flow months (Table 4).

3.6.4 Validation of EF methods

In this study, we reviewed, adapted and developed five hydrological EF methods and tested them on 11 case studies. In addition, the performance of the 5 hydrological methods was tested against the locally-calculated EFRs by using the efficiency coefficient $R2$ from Nash and Sutcliffe (1970). In extremely dry conditions ($MMF<1m^3.s^{-1}$), there is no environmental flow allocation.

3.7 Description of the global hydrological model LPJml and simulations

The global application and comparison of different EF methods requires the simulation of “pristine” river discharge. For that, the Lund-Potsdam-Jena managed land (LPJml) model was used to simulate river flow globally at a spatial resolution of 0.5’ by 0.5’ on a daily time step. The CRU TS 2.1 global climate data (1901–2002) was used to drive the model. LPJml was initially a dynamic global vegetation model simulating water and carbon balances for natural vegetation (Sitch et al., 2003, Gerten et al., 2004). Different from other GHMs such as VIC (Liang et al., 1994) and HO8 (Hanasaki et al., 2008), LPJml has been extended with a crop model (Bondeau et al. 2007, Fader et al., 2010), with a river routine that simulates water withdrawal from rivers and lakes (Rost et al., 2008) and more recently with the integration of a dam and reservoir module (Biemans et al., 2011).

Simulations were computed from 1901 to 2001 with a spin-up phase of 1000 years for carbon and water balance. A simulation was run for naturalized river flow by using exclusively potential natural vegetation (PNV). EFRs calculations were always computed with natural flows obtained from historical datasets or from simulated naturalized flow datasets. All the analyses were done on a monthly time step. In order to compare EF methods globally, the ratio of monthly EFRs to natural monthly flow was used to show the intra-annual variability of EFRs in space and time. Calculations are shown on an annual basis and for two months: January and April averaged from 1961 to 2000. We also compared the annual ratio of EFRs on natural flow of different river basins by giving a range of annual EFRs with the 5 hydrological methods.

4 Results

4.1 Comparison of environmental flow methods per case study

The overall annual average of EFRs across the 11 case studies and 5 methods represent 37% of MAF (Figure 2; Table 5). The range of EFRs defined locally in the case studies is from 18 to 63% of MAF while the range of EFRs among the global EF methods is from 9 to 83% of MAF. On average, low-flow requirements represent 46 to 71% of mean low-flows while high-flow requirements represent 17 to 45% of high-flows (Table 5). Low-flow requirements are usually higher than high-flow requirements relatively to mean annual flow when the low-flow season is longer than 4 months. The correlation between the EFRs calculated with the 5 selected methods and the locally-calculated EFRs are shown in Figure 3. Among EF methods used, all the simulated EFRs were highly correlated with the locally-calculated EFRs. The Tessmann and VMF methods recorded the highest correlation coefficient (R^2=0.91) and Smakhtin, Q_{90}_Q_{50} and Tennant methods showed a correlation (R^2) between from 0.86 and 0.88.

On average, the Tennant method allocated about 10% less water than the locally-calculated EFRs. The Tessmann method was in general above the locally-calculated EFRs (+24%), especially in polar freshwater ecosystems (above 100%). Smakhtin method allocated less water than recommended in xeric freshwater and tropical freshwater ecosystems (variable river regimes) and allocated more water than recommended in polar freshwater zones (stable river regime). Similarly, the Q_{90}_Q_{50} method allocated less water than recommended to the variable river regimes and more water than recommended to stable river regimes (about 100%). Finally, the VMF method was closest to the recommended EFRs (about 10% above average). All the hydrological methods gave lower EFRs estimates than the locally-calculated EFRs in xeric freshwater ecosystems and gave higher estimates of EFRs than locally-calculated EFRs in polar freshwater ecosystems. The methods that were closer to the locally-calculated EFRs for xeric freshwater ecosystems were Tessmann and the VMF methods and the Tennant method for polar freshwater ecosystems. For temperate coastal rivers, the method that was the closest to the locally-calculated flow was the VMF method (Figure 2; Table 5).

EFRs of variable rivers accounted for more than 60% of the total annual flow during the high-flow season. For example, in the case of the BWR and Iranian case studies, about 80% of the river flow occurs during the high-flow season which lasts between 3 to 5 months. In the Tanzanian case, high-flow season lasts 5 months during which 90% of the total flow occurs and about 80% of EFRs are allocated. The Tessmann, VMF and Q_{90}_Q_{50} methods were in line with the locally-calculated EFRs of variable rivers, but, only the VMF and Tessmann methods could capture the intra-annual variability and allocated peak flows during the high-flow season (Figure 2; Table 5). The Tennant and Smakhtin methods allocated enough water during the low-flow season but less than the locally-calculated EFRs during the high-flow season. In cases where the locally-calculated EFRs were defined with a fixed minimum annual flow threshold such as in the Ipswich river case, all the hydrological EF methods allocated more water than the locally-calculated EF method.

In perennial rivers, such as the Chilean case study, all the monthly flows were considered as high-flow months (MMF was always above MAF) and about 40% of the total flow occurs during the three wettest months of the year with the allocation of more than 50% of EFRs. The Tessmann, Tennant and VMF methods were in line with the locally-calculated EFRs at the exception of the Smakhtin and the $Q_{90}\_Q_{50}$ methods which allocated more water than recommended. In the Odzi River in Zimbabwe, only Tessmann and $Q_{90}\_Q_{50}$ could allocate an amount of water close to the locally-calculated EFRs. In the Voijm River, in Sweden, all the EF methods used were in line with the locally-calculated EFRs at the exception of the timing of the peak flow which was calculated two months later with the locally-calculated EFRs.

4.2 Comparison of environmental flow methods globally

Among the methods, EFRs ranged from 25 to 46% of MAF, with increasing percentage of EFRs from the Smakhtin method to the $Q_{90}\_Q_{50}$ method. On a monthly basis, the VMF, Tennant and Tessmann methods produced similar spatial distribution of EFRs. Similarly, the Smakthin and Q90_Q50 methods showed analogous spatial allocation of EFRs. With the Tessmann and VMF methods, high percentages of MMF were allocated to EFRs during the low-flow season (between 60% and 100% of MMF respectively) compared with other methods. With Smakhtin and $Q_{90}\_Q_{50}$ methods, water allocation was very high in certain areas of the tropics and of the poles (close to 100% of MMF) whereas in areas characterized by a variable flow, EFRs had a very low to no-flow allocation such as in India (Figure 4). The Smakhtin method allocated 100% of MMF in the regions of the artic pole, between 40% to 60% of MMF in the tropics and between 0 and 40% of the MMF in the rest of the world. The VMF method, Tennant and Tessmann methods allocated at least from 20 to 40% of MMF in arid regions and more than 50% of the MMF during the low-flow season. The Tennant method calculated high EFRs in the tropics (EFRs≥100% of MMF). However, the Tennant method calculated lower EFRs than the rest of the methods in temperate zones especially during high-flow period. In those temperate zones, the Tennant method allocated about 20% of MMF while the VMF and Tessmann methods allocated at least 40% of MMF. By comparing Figure 4 with Figure 5 and 6, it becomes clear that EFRs are more homogenous on an annual compared to a monthly basis because monthly EFRs are averaged-out. For example, the Tessmann method allocated an equal percentage of MAF worldwide and did not show strong differences between regions, whereas, on a monthly basis, the Tessmann method showed clear spatial differences in flow allocation.

A comparison of EF methods at the outlet of 14 of the biggest river basins shows that perennial rivers such as the Congo, Amazon, Rhine and Mississippi required between 30 to 80% of MAF (Figure 7). More variable river basins such as the Ganges or the Nile required between 10 to 50% of MAF depending on the five EF methods. On average, $Q_{90}\_Q_{50}$ resulted in the highest EFRs (48% of MAF) and the Smakhtin method resulted in the lowest EFRs (26% of MAF). The VMF method allocated on average 33% of MAF which is higher than the Tennant method (30% of MAF) and lower than the Tessmann method (43% of MAF).

5 Discussion

5.1 Improving global environmental flow assessments

This is the first global study that compared different hydrological methods for calculating EFRs while accounting for intra-annual variability. Those hydrological methods were 'validated' with a set of local case studies to identify methods that could be used in future global water assessments. The inclusion of intra-annual variability into the algorithm of EF methods presents a significant improvement compared to previous global water assessments based on an annual scale (Smakhtin et al., 2004;Vorosmarty et al., 2010). The VMF method was developed with the specific aim of being flexible, reliable and globally applicable. The VMF and Tessmann showed a good correlation with the locally-determined EF in different case studies from a wide range of climates, flow regimes and freshwater ecosystems (R^2 =0.91). Both methods classify flow regime into high, intermediate and low-flow seasons and allocate monthly EFRs with different percentages of the MMF or MAF. Those two methods show some temporal and spatial improvements in the calculation of EFRs, especially for the variable flow regimes compared with methods using annual flow thresholds such as low-flow indices (Q_{90} or 7Q10) or percentages of MAF (Palau, 2006). The advantage of the VMF and the Tessmann methods is that they mimic the natural flow as suggested by Poff et al. (2009). In the case of the VMF method, the allocation of 30 to 60% of mean monthly flow as a degradation limit was selected because the purpose of this study was to allocate water for freshwater ecosystems in "fair" ecological conditions similar to Smakhtin et al. (2004) and allocation of 30% of MAF to calculated EFRs was widely recognized (Hanasaki et al., 2008).

5.2 Differentiation between Tessmann and VMF methods

The main difference between the VMF and Tessmann methods is that they define high-flow, intermediate-flow and low-flow seasons with different algorithms (Table 4). They allocate respectively 60% and 100% of MMF during the low-flow season. Relative amount of EFRs during low-flow period is high because we considered that habitat area for freshwater ecosystems is smaller during the low-flow season compared to the high-flow season and we wanted to prevent eventual impact of seasonal droughts on freshwater ecosystems (Bond et al., 2008). Saving water for the environment is thus more important during the low flow season in order to reduce the pressure on fish survival. This assumption is confirmed in the study of Palau and Alcázar (2010) where our calculated LFRs were close to the requirements of fish habitat survival. The VMF method allows other water users to withdraw up to 40% of monthly flow during the low-flow season. Hence, water users such as industries and irrigation sector can still withdraw water during the low-flow season (which is usually the season with the highest water demand from the irrigation section) whereas with the Tessmann method, water withdrawals are not possible during the low-flow season. During the high-flow season, allocation of HFRs do not differ significantly between the VMF and Tessmann methods as the VMF method allocates 30% of MMF and the Tessmann method allocates 40% of MMF. The determined threshold levels of the VMF method can easily be adjusted depending on the objectives of the water policy (e.g. a stricter policy on riverine ecosystems may require higher EFRs thresholds), on the ecological status of a river basin (a very altered river may never achieve the actual thresholds of VMF) and on the specific demands of other water users.

5.3 Limitations of environmental flow methods based on annual thresholds

The three other methods used either percentages of annual flow (Tennant) or annual flow quantiles (Smakhtin and Q90_Q50) to allocate EFRs. Compared to methods based on monthly values such as Tessmann and VMF methods, we found that EFRs calculated with methods based on annual thresholds (Tennant, Smakhtin and Q90_Q50 methods) were lower during low-flow season and higher during high-flow season than the locally-calculated EFRs. Using annual flow quantiles to calculate EFRs is not appropriate for certain type of flow regimes. For example, by using the Q90_Q50 or the Smakhtin method, the calculated EFRs was always lower than the locally-defined EFRs of variable rivers and was always higher than the locally-defined EFRs of perennial rivers (Fig. 2). In this study, we showed that using a parametric EF method such as a percentage of flow was more appropriate than non-parametric methods such as flow quantiles. The Tennant method did not perform well in tropical case studies because this method was developed for temperate rivers. For example, the calculated EFRs using the Tennant method were lower than the locally-calculated EFRs during the high-flow season of rivers with variable flow regimes. The flow quantile methods, such as the Smakhtin and $Q_{90}\_Q_{50}$ methods, showed that, in perennial rivers such as in the Chilean case, there was a higher allocation of EFRs compared to other methods (Figure 1, 3, 4, and 5). In variable rivers, the $Q_{90}\_Q_{50}$, Smakhtin and Tennant methods showed a lower allocation of EFRs during the high-flow season and a higher allocation of EFRs during the low-flow season compared to the locally-calculated EFRs (Table 5). Similarly, those methods did not seem appropriate for ephemeral and intermittent rivers because the river would be flooded during the dry season, which can increase the risk of invasion of exotic species (O'Keeffe, 2009). Furthermore, Botter et al. (2013) agreed with the fact that allocating fixed minimum flows to erratic flow regimes was not appropriate; owing that those flow regimes have a high-flow variability and allocating a fixed minimum flow would be disproportionate to the incoming flows during the low-flow season. Furthermore, flow quantile methods are not flexible enough because the allocation of higher flow quantiles than Q_{90} for LFRs such as Q_{75} and Q_{50} as suggested in Smakhtin et al. (2004) did not improve EFRs on a monthly and annual basis because EFRs were often higher than average flow especially in the case of perennial rivers (data not shown).

5.4 Differences of EFRs allocation among river regime types

Estimates of EFRs with the five EF methods all showed strong differences in water allocation in space and time. For example, polar freshwater and xeric freshwater ecosystems require different absolute amount of EFRs during the year depending on the flow season (Figure 2). In addition, in some cases such as the Iranian case, with the locally-calculated EFRs, we can see that the amount of water is available for other users during the dry season is limited and will probably conflict with irrigation demand. In contrast, the flow of the Chilean case study is constant during the whole year such as the locally-calculated EFRs. The Tessmann and VMF methods showed to cope well with defining EFRs of different flow regimes.

5.5 Monitoring and systematisation of future EFR studies

Environmental flow method development is still at an early stage and EFRs are only determined in few places of the developed world and are hardly included in water management and governance (Pahl-Wostl et al., 2013;Acreman and Ferguson, 2009;Palau, 2006). In developing countries, ecological surveys and hydrological data are often absent because nature conservation including freshwater ecosystems is often not a priority (Benetti et al., 2004). Despite some recent attempts to relate freshwater ecosystems datasets with different flow components globally (Yoshikawa et al., 2013;Xenopoulos et al., 2005), additional efforts are required to develop a systematic regional environmental flow framework based on multi-disciplinary methods (Poff et al., 2009;Pahl-Wostl et al., 2013).

5.6 Social aspects of environmental flow requirements

Environmental flow requirements are, in the end, a societal decision which is often made at local scales and quantification of EFRs depends on the level of protection that is desirable by society/policy. However to develop a global EF method at global scale we need a quantification method which can be used in global water resources models. We decided to develop a method that reflects a level of ecosystems described as ‘fair ecological conditions’ as in Smakhtin et al. (2004). Including social and political decisions in quantitative assessment is very difficult and beyond the aim of this paper. At the moment, we cannot possibly address this full new research agenda but we limited ourselves to the quantification of EFRs as a function of biophysical parameters. However, we acknowledge that there is a need for a more systematic EF method that would link the natural and social science fronts and would create a unifying framework for the assessment and implementation of sustainable EFRs in national water policy (Pahl-Wostl et al., 2013).

5.7 Limitations of our study

The choice of EF methods for our study was limited to hydrological methods due to lack of data on ecosystem responses to flow alterations for most river basins of the world. This lack of ecohydrological data makes it difficult to determine minimum environmental flow thresholds and tipping points of different freshwater ecosystem across the world. An improved consistent ecohydrological monitoring and forecasting system is required in order to develop a global river classification system, which would account for the sensitivity of the respective aquatic ecosystems to flow modifications (Barnosky et al., 2012). In order to go beyond previous individual un-related case studies we consistently applied different EF methods across a set of existing case studies located in different climates and freshwater ecosystems regions. Amongst the 200 existing EF methods, it is difficult to find case studies, which quantify the sensitivity of freshwater ecosystems to change in discharge. It would be a great improvement if the number of case studies could be increased in order to increase the level of validation and find more accurate algorithms per ecoregion. For example, a higher allocation of flow might be required in perennial tropical rivers due to their high biodiversity index (Oberdorff et al., 2011) and due to their lower hydrological resilience to climate fluctuation compared to rivers with more variable flow regimes (Botter et al., 2013). We are aware of the heterogeneity of the case studies in term of inter-annual variability, and, for that reason, we chose case studies with at least a minimum of 15 years of hydrological data, which is sufficient to capture inter-annual variability according to Kennard et al. (2010). However, none of the EF methods used in this study were explicitly accounting for daily high and low flood pulses, which often drive riparian vegetation (Shafroth et al., 2009).

5.8 Refining global water assessments

Given the lack of global datasets on riverine ecosystems and river hydraulics, the use of the monthly EF methods such as the VMF or Tessman method is recommended for global application In the case that policymakers aim at achieving good to excellent ecological status, we recommend to increase EFRs by allocating a higher percentage of MMF such as the method developed by Richter et al. (2012). This study did not aim at refining locally-determined EF methods but at identifying one or several methods for global application. Due to these new estimates of EFRs, improved global water availability assessments can better inform other water users. Also expansion of irrigated lands can be carried out in a more sustainable way by accounting for current and future water availability constrained by EFRs. The VMF method estimated that at least 40% of global annual flow should be reserved for environmental flows to keep ecosystems in “fair” ecological conditions, but that does not necessarily mean that the 60% of the water left should be used by other users. It is important to acknowledge that this is a global annual average and that EFRs highly vary depending on the region and the flow season. Finally, there is no EFRs benchmark existing at a river basin scale. That is why we show in Figure 7 a range of annual EFRs at a river basin scale by using the five hydrological EF methods. The VMF method is always within the range of the five hydrological methods compared with methods such as $Q_{90}\_Q_{50}$ which tend to allocate lower estimates of LFRs than with the locally-calculated EFRs.

In some river basins, the actual flow is already highly altered (Western US, South and East Asia) so future increases in water withdrawals have to be carefully assessed from an EF point of view (data not shown). Future global EF assessments should be carried out on a monthly basis rather than annual basis to determine accurately freshwater ecosystem and irrigation demands. Particular attention should be paid to highly modified rivers where water withdrawals represent more than 60% of their annual river flow such as the Ganges, because EFRs will probably not be met in such conditions. Free-flowing tropical rivers such as the Amazon should also be preserved since they account for the highest biodiversity index and were assessed to be vulnerable to fluctuations in river discharge caused by land use change and climate change (Botter et al., 2013). Addressing EFRs which is part of a pro-active management of river basins is certainly a less costly solution than using reactive solutions such as river restoration measures (Palmer et al., 2008).

5.9 To be considered in future EF assessments

In future global EF assessments, it is important to consider the inter-annual variability of flow regimes because EFRs are most of the time calculated on a long period average (> 20 years) and EFRs might need to be refined for dry years (Hessari et al. (2012)). Regarding the use of ecological datasets, it is worth considering the delay in ecosystem response related to flow events when calculating EFRs (Sun et al., 2008).

6 Conclusion

We tested five different hydrological environmental flow methods for their applicability in global water assessments and found the VMF method to be a valid and easy method for implementation in global hydrological models. The VMF methods uses a simple algorithm and also takes into account intra-annual variability. It improves environmental flow calculations due to its increased time resolution from an annual to monthly basis and its global applicability. The VMF method was validated with existing EFR calculations from local case studies and showed good correlations locally determined EFRs. This validation increases our confidence to use this method in global water assessments. The VMF method fits many different flow regimes thanks to its algorithm determining low, intermediate and high-flows and it is recommended to use it in future global water assessment especially in the case of variable flow regimes. The use of different methods, such as the five methods tested in this paper, can provide a range of calculated EFRs at global and river basin scale in ‘fair’ ecological conditions. Including EFRs in future global water assessments will improve the estimates of global water boundaries and will enable the production of sustainable scenarios on the expansion of irrigated land and on the use of water for other users such as the hydropower sector.

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Table 1: Description of regional environmental flow methods

Type of EF method	Data input	Example	Sources
Hydrological	Long-term datasets of unregulated or naturalized daily flows (> 20 years)	Tennant, Tessman, IHA, RVA, DRM, ABF	(Babel et al., 2012;Smakhtin et al., 2006;Tennant, 1976;Tessmann, 1980;Richter et al., 1997;Richter, 2010;Armstrong et al., 1999)
Hydraulic	Flow velocity, river crossing area	R2Cross method	(Armstrong et al., 1999)
Habitat-simulation	Flow velocity, river cross section, dataset of a fish specie	PHABSIM, IFIM	(Capra et al., 2003;Milhous, 1999;Bovee, 1986;Bovee et al., 1998)
Holistic	Combination of hydrological, hydraulics, ecological and social sciences (expert knowledge)	Building block method (BBM), ELOHA, DRIFT	(Hughes, 2001;King and Louw, 1998;Arthington et al., 2006;Poff et al., 2009;Bunn and Arthington, 2002)

Table 2: Description of geographic coordinates of the case studies and their hydrological datasets

Case studies	Latitude	Longitude	Daily flow data used in case studies	Daily flow data used in this study
Bill William river, US (Shafroth et al. 2009)	34.23	-113.60	Pre-dam data (1940-1965)	GRDC 4152120
Ipswhich river, US (Armstrong et al. 1999)	42.57	-71.03	Ipswhich flow data (1961-1995)	20 years LPJml simulation without landuse and irrigation (PNV run)
Silvan river, Spain (Palau and Alcázar, 2010)	42.37	-6.63	Natural flow data (1980-1998): no flow regulation	Dataset from the authors
Osborne river, Zimbabwe (Symphorian et al., 2003)	-18.75	32.25	Naturalized flow data (1961-1973)	Dataset from the authors
Voijm dam, Sweden (Renofalt et al., 2010)	62.80	17.93	Pre-dam data (1909-1940)	Dataset from the authors
Newhalen river, Alaska (Estes, 1998)	59.25	-154.75	Pre-dam data (1951-1986)	USGS 153000000
Hong Kong, China (Niu and Dudgeon, 2011)	22.27	113.95	Natural flow data (2007-2008)	20 years LPJml simulation without landuse and irrigation (PNV run)
la Gna river, Vietnam (Babel et al., 2012)	10.82	107.15	Pre-dam data (1977-1999)	Dataset from the authors
Great Ruaha river, Tanzania (Kashaigili et al., 2007)	-7.93	37.87	Pre-dam data (1958-1973)	20 years LPJml simulation without landuse and irrigation (PNV run)
Huasco river, Chile (UICN, 2012)	-28.43	-71.20	Historical data (1975-1988)	Dataset from the authors
Sharh Chai river, Iran (Yasi et al., 2012)	37.70	45.32	Pre-dam data (1949-2004)	Dataset from the authors

Table 3: Inter-comparison of hydrological indicators of the case studies.

Case studies	Major Habitat Type (Abell et al., 2009)	Environmental flow method type[1]	MAF[2] (LF[3]-HF[4])	BFI [5]	HVI[6]	Nb. high-flow months	Nb. intermediate months	Nb. low-flow months
Bill William river, US (Shafroth et al. 2009)	Xeric freshwater	4. HEC-EFM	2.7 (0.8-5.3)	5.3	2	6	0	6
Sharh Chai river, Iran (Yasi et al, 2012)	Xeric freshwater	1. GEFC (class C)	5.3 (1.6-12.7)	21.1	3.3	4	1	7
Ipswhich river, US (Armstrong et al. 1999)	Temperate coastal river	2. R2Cross method	265 (120-556)	22.6	1.3	5	2	5
Silvan river, Spain (Palau and Alcázar, 2010)	Temperate coastal river	3. RHYHABSIM (class B)	0.7 (0.3-0.9)	21.5	0.9	7	2	3
Osborne dam, Zimbabwe (Symphorian et al., 2003)	Temperate coastal river	1. Hugues method (class B)	39.7 (25.2-55.8)	43.6	0.6	5	5	2
Huasco river, Chile (Pouilly and Aguilera, 2012)	Temperate coastal river	3. PHABSIM	6.2 (5.3-8.9)	80.6	0.2	12	0	0
Voijm dam, Sweden (Renofalt et al., 2010)	Polar freshwater	4. Expert knowledge	39 (16.3-71)	51.3	0.7	6	2	4
Newhalen river, Alaska (Estes, 1998)	Polar freshwater	1. Tennant (fair/degrading class)	284 (98.1-544.3)	21.5	2.2	5	2	5
Hong Kong, China (Niu and Dudgeon, 2011)	Tropical floodplain	3. Macroinvertebrates sampling (degrading and outstanding classes)	1119 (317-1921)	12	1.6	6	2	4
La Gna river, Vietnam (Babel et al., 2012)	Tropical and subtrop. coastal river	1. RVA approach (*Q25-Q75*)	133.5 (49.4-251.3)	15.4	1.7	5	1	6
Great Ruaha river, Tanzania (Kashaigili et al., 2007)	Tropical and subtrop. coastal river	1. Desktop Reserve Model (class C/D)	245 (45-524.4)	6.4	4.3	5	1	6

1. Environmental flow method type: 1. hydrological, 2. hydraulic 3. habitat simulation, 4. Holistic,
2. MAF: Mean Annual Flow (m3/s)
3. LF: Low-flow average calculated as the average flow when MMF≥MAF (m3/s)
4. HF: high-flow average calculated as the average flow when MMF≤MAF (m3/s)
5. Baseflow index: Q_{90}/MAF (see eq.1)
6. Hydrological variability index: (Q_{25}-Q_{75})/Q_{50} (see eq. 2)

Table 4: Description of tested hydrological environmental flow methods with MAF the Mean Annual Flow, MMF the Mean Monthly Flow, Q90 the flow exceeded 90% of the period of record and Q50 the flow exceeded 50% of the period of record. HFRs, IFRs and LFRs are respectively used to high, intermediate and low-flow requirements.

Hydrological season	Smakhtin (2004)	Tennant (1976)	Q90_Q50 (2013)	Tessman (1980)[b]	Variable Monthly Flow (2013)[c]	Hoekstra (2012)
Determination of low-flow months	MMF<= MAF	MMF<= MAF	MMF<= MAF	MMF<= 0.4*MAF	MMF<= 0.4*MAF	-
Low-flow requirements (LFRs)	Q90	0.2* MAF	Q90	MMF	0.6*MMF	0.8*MMF
Determination of high-flow months	MMF>MAF	MMF>MAF	MMF>MAF	MMF>0.4*MAF & 0.4*MMF>0.4*MAF	MMF> 0.8*MAF	-
High-flow requirements (HFRs)	0 to 0.2*MAF[a]	0.4*MAF	Q50	0.4*MMF	0.3*MMF	0.8*MMF
Determination of intermediate-flow months	-	-	-	MMF>0.4*MAF & 0.4*MMF<= 0.4*MAF	MMF> 0.4*MAF & MMF<= 0.8*MAF	-
Intermediate-flow requirements (IFRs)	-	-	-	0.4*MAF	0.45*MMF	-

a. If Q90>30%MAF, HFRs=0,
If Q90<30% and Q90>20%, HFRs=7%MAF,
If Q90<20% and Q90>10%, HFRs=15%MAF,
If Q90<10%, HFRs=10%MAF.

b. Only the Tessmann and the Variable Monthly Flow methods require intermediate-flow determination as their methods are based on monthly flows. The other methods (Smakhtin, Tennant and Q90_Q50) only allocate EFRs in high and low-flow seasons and finally Hoekstra method does not distinguish between high-flow and low-flow season.

Table 5: Comparison of annual average of environmental flow requirements (EFRs) per method and per case study (EFR: Environmental flow requirements, LFR: Low-flow requirements, HFR: High-flow Requirements) – EFR is expressed in percentage of mean annual discharge of river in "natural" conditions, LFR is expressed in percentage of mean annual low-flow, HFR is expressed in percentage of mean annual high-flow.

Case studies	MHT class (Abell et al., 2009)	EFR case study (LFR and HFR)	Variable Monthly Flow (LFR and HFR)	Smakhtin (LFR and HFR)	Tennant (LFR-HFR)	Tessmann (LFR-HFR)	Q_{90}_Q_{50} (LFR-HFR)	Average all EFR results (average LFR-average HFR)
Bill William river, US (Shafroth et al., 2009)	Xeric freshwater	63 (133 - 48)	33 (46-30)	12 (18-11)	27 (67-18)	46 (72-40)	6 (18-3)	46 (48-26)
Sharh Chai river, Iran (Yasi et al., 2012)	Xeric freshwater	51 (42-53)	35 (56-30)	19 (70-15)	27 (66-17)	50 (90-40)	19 (70-13)	33 (66-28)
Ipswhich river, US (Armstrong et al., 1999)	Temperate coastal river	25 (56-12)	35 (47-30)	25 (50-14)	27 (44-19)	49 (60-30)	37 (44-19)	33 (46-17)
Silvan river, Spain (Palau and Alcázar, 2010)	Temperate coastal river	34 (58-28)	34 (50-30)	26 (54-20)	33 (56-28)	46 (73-40)	77 (89-74)	43 (63-37)
Osborne dam, Zimbabwe (Symphorian et al., 2003)	Temperate coastal river	46 (84-13)	32 (44-27)	44 (73-26)	27 (34-24)	46 (66-35)	59 (73-53)	44 (62-29)
Huasco river, Chile (Pouilly and Aguilera, 2012)	Temperate coastal river	34 (30-42)	30 (30-30)	81 (94-56)	25 (23-28)	44 (47-44)	83 (94-64)	54 (53-45)
Voijm dam, Sweden (Renofalt et al., 2010)	Polar freshwater	20 (18-21)	34 (45-30)	51 (123-28)	28 (48-22)	48 (72-40)	69 (123-52)	43 (71-32)
Newhalen river, Alaska (Estes, 1998)	Polar freshwater	18 (27-14)	35 (53-30)	20 (62-15)	32 (58-21)	30 (88-40)	50 (63-29)	30 (59-25)
Hong Kong, China (Niu and Dudgeon, 2011)	Tropical floodplain	48 (77-44)	53 (50-30)	19 (42-16)	30 (71-23)	40 (82-40)	53 (42-54)	38 (67-32)
La Gna river, Vietnam (Babel et al., 2012)	Tropical and subtrop. coastal river	53 (50-54)	35 (52-30)	28 (31-9)	28 (54-21)	48 (75-40)	38 (42-38)	39 (51-32)
Great Ruaha river, Tanzania (Kashaigili et al., 2007)	Tropical and subtrop. coastal river	22 (19-22)	33 (54-30)	9 (35-6)	28 (109-19)	46 (92-40)	19 (58-17)	25 (61-19)
Average per method		37 (43-28)	40 (48-30)	31 (59-20)	32 (57-22)	40 (74-39)	43 (65-38)	37 (56-34)

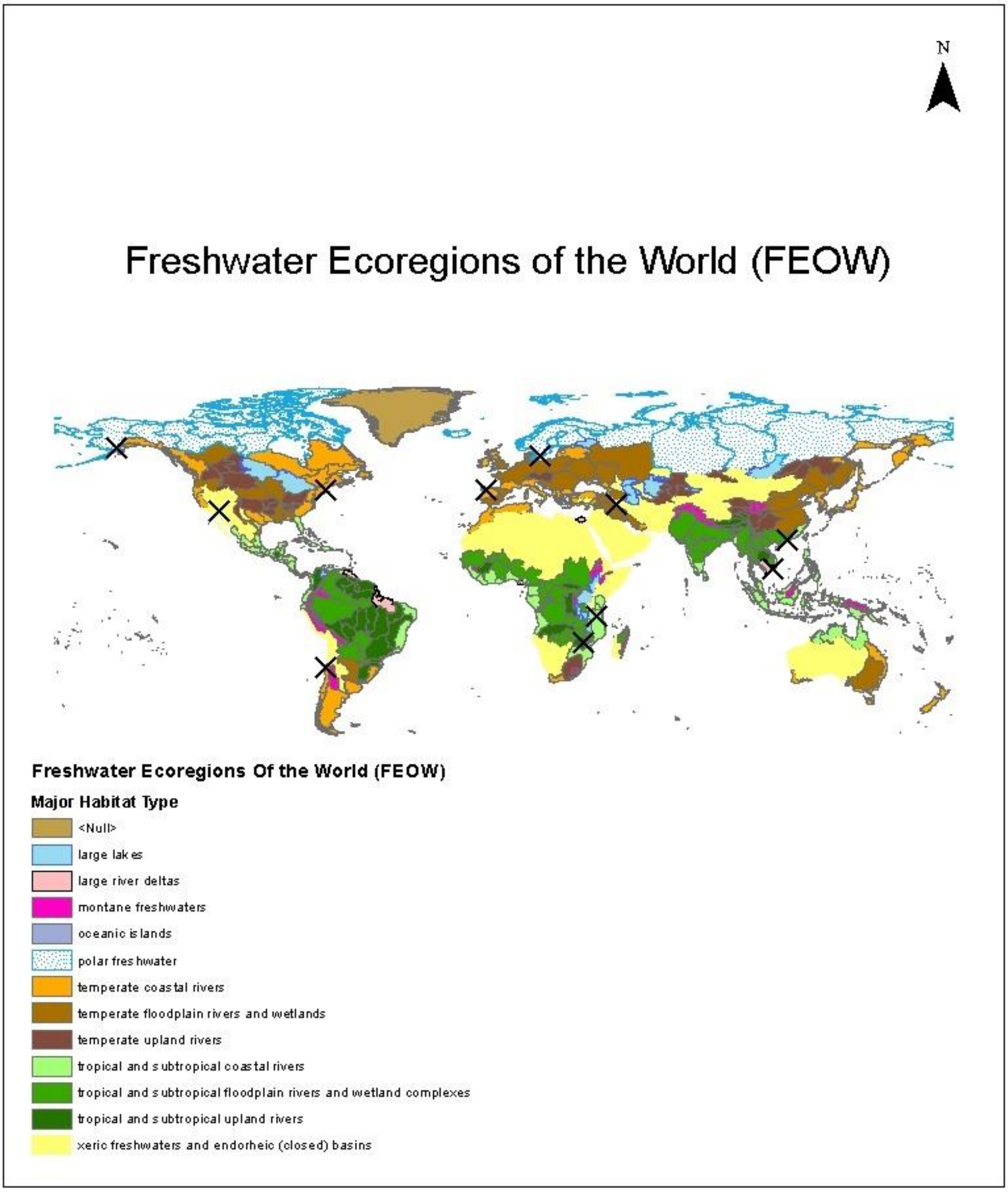

Figure 1. Location of 11 case studies where environmental flow requirments (EFRs) were locally defined.

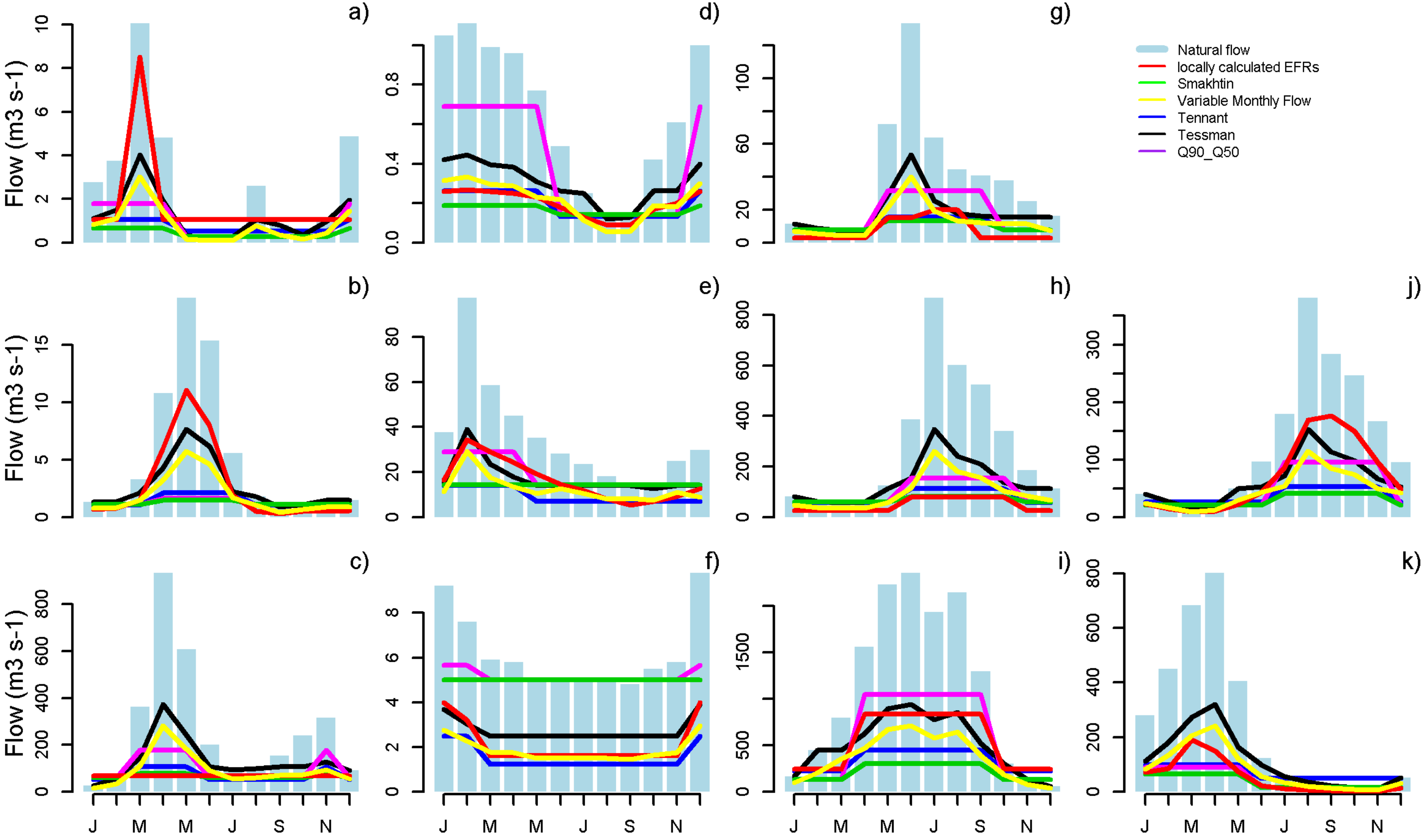

Figure 2: Comparison of EF methods with locally-calculated EFRs in different case studies a) BWR, US, b) Urmia dam,Iran c) Ipswhich river, US, d) Silvan river, Spain, e) Osborne dam, Zimbabwe f) Huasco river, Chile g) Voijm dam, Sweden, h) Newhalen river, Alaska, i) Hong Kong stream, China, j) Gna river, Vietnam, k) Great Ruaha river , Tanzania. In light blue, observed or simulated natural flows from case studies are presented except for natural flows c) and e) which were simulated with LPJml.

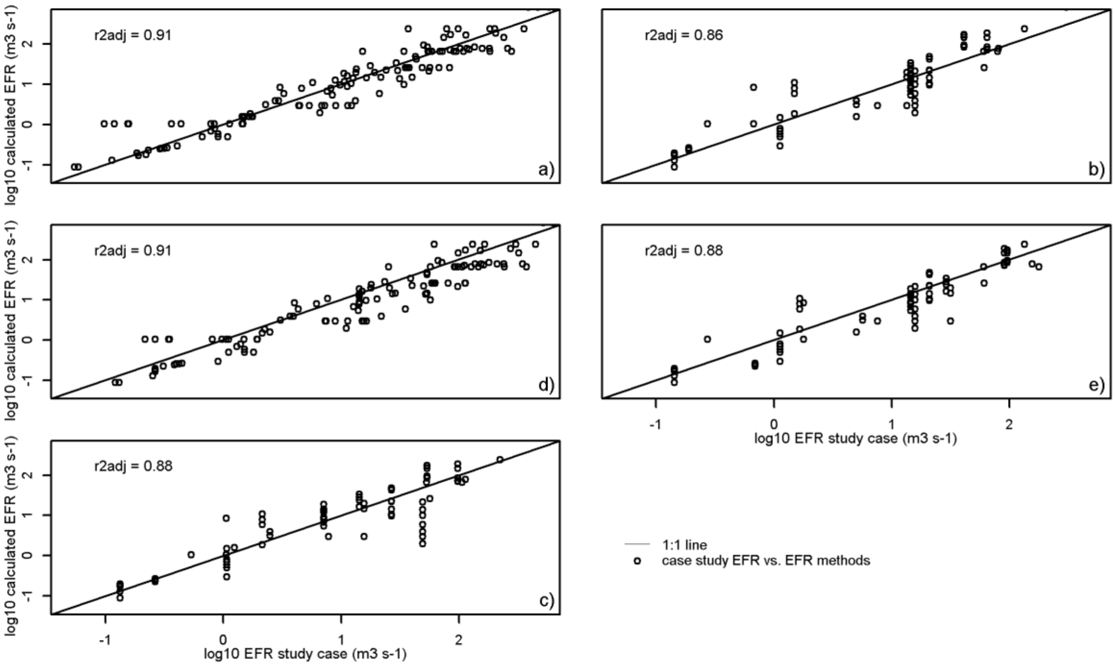

Figure 3: Relation between the monthly calculated EFRs and the locally-calculated monthly EFRs of 11 case studies with (a) Variable Monthly Flow, (b) Smakhtin, (c) Tessmann, (d) Q90_Q50, (e) Tennant methods. In each sub-figure, each dot represents EFRs for one month and for one case study.

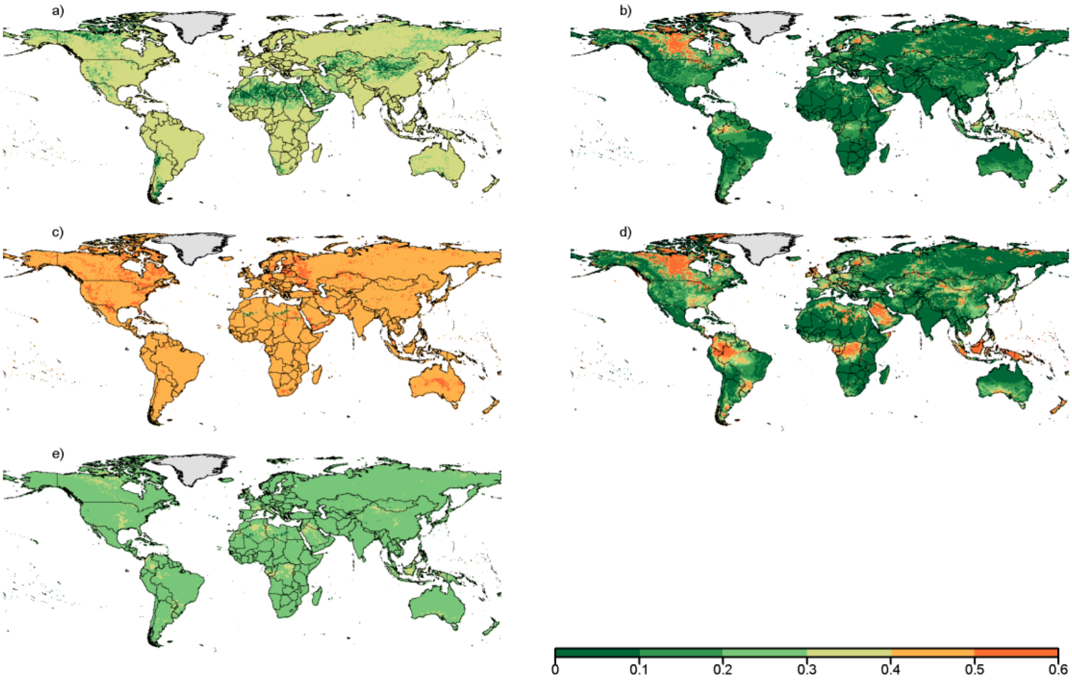

Figure 4: Ratios of annual environmental flow by annual natural flow within a) Variable Monthly Flow , b) Smakhtin, c)Tessmann, d)Q90_Q50, e) Tennant environmental flow methods

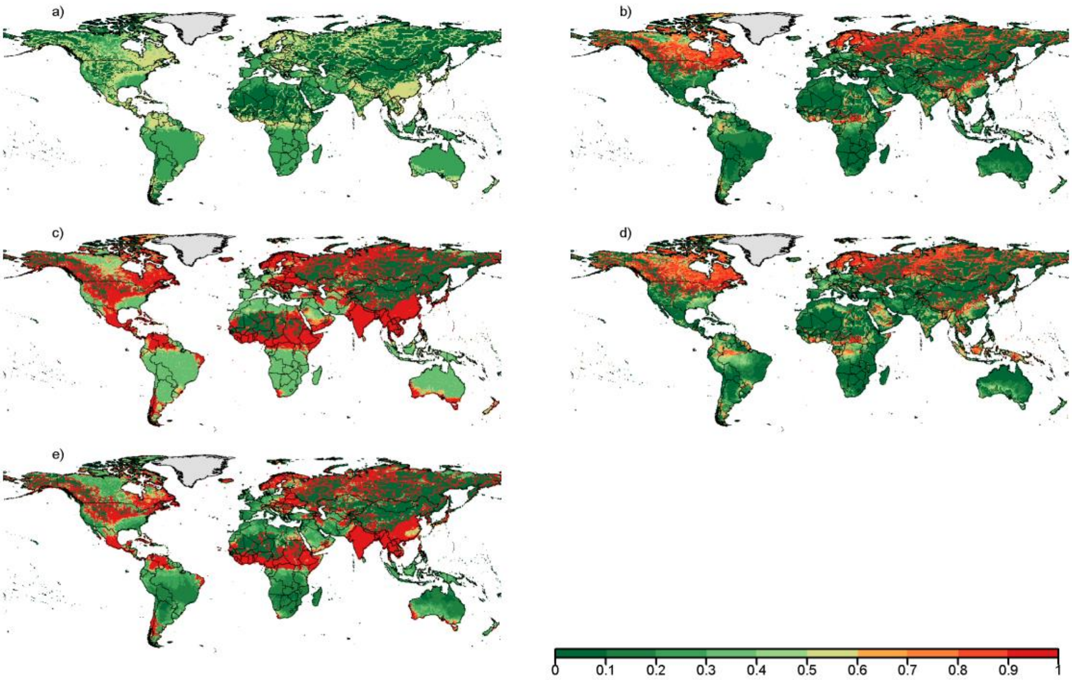

Figure 5: Ratios of monthly environmental flow by monthly actual flow (January) within a) Variable Monthly Flow , b) Smakhtin, c)Tessmann, d)Q90_Q50, e) Tennant environmental flow methods

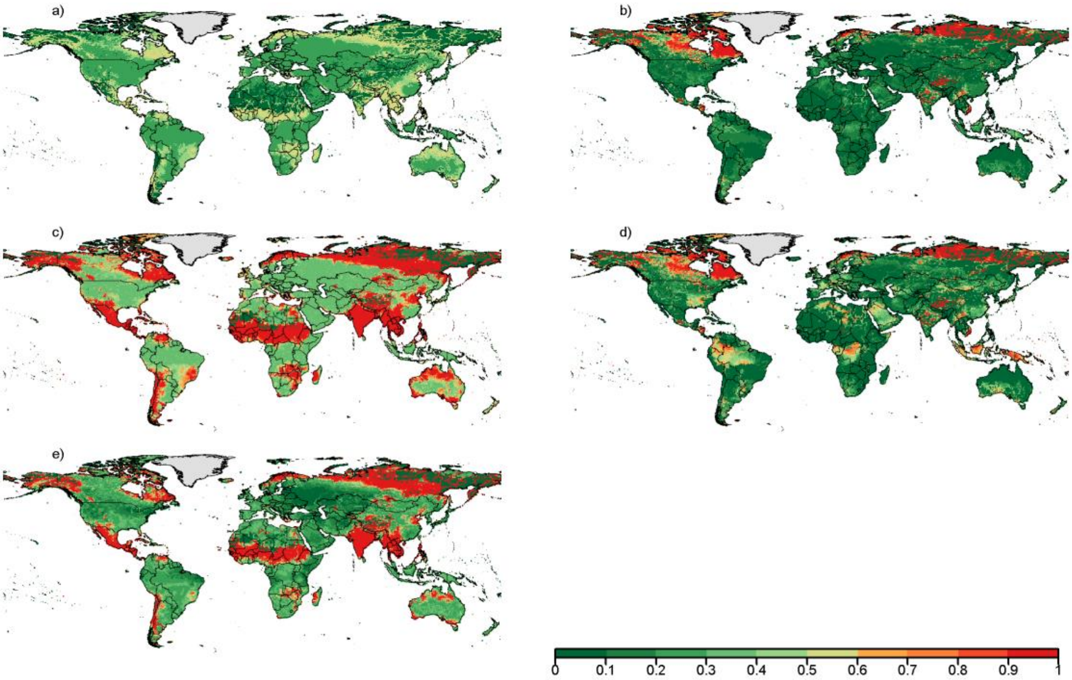

Figure 6: Ratios of monthly environmental flow by monthly actual flow (April) within a) Variable Monthly Flow , b) Smakhtin, c)Tessmann, d)Q90_Q50, e) Tennant environmental flow methods

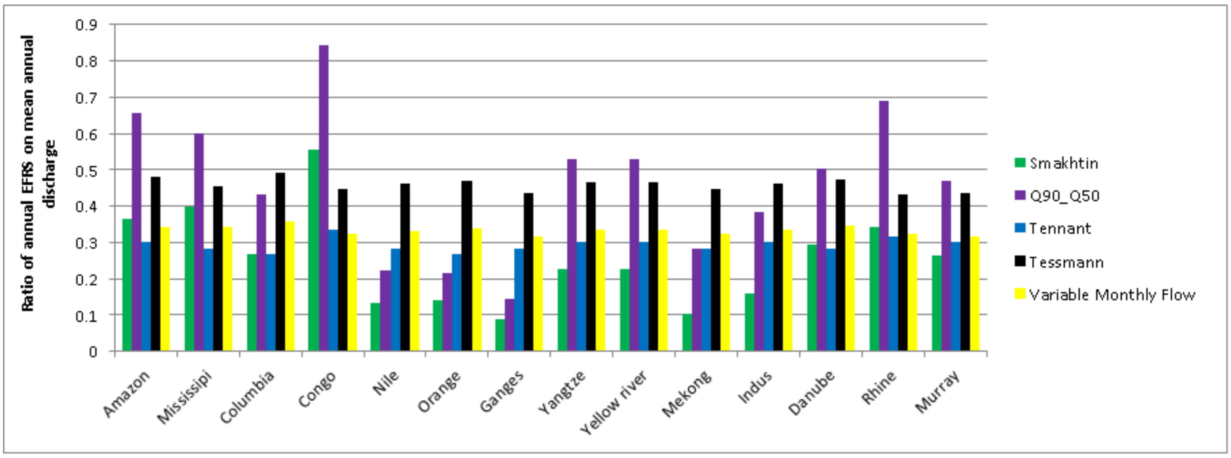

Figure 7: Comparison of 5 environmental flow methods at the outlet of 14 river basins.