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Discussions

Accounting for environmental flow requirements in global water assessments

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Abstract

With growing water needs for food production, it is necessary to improve the quantification of "Environmental Flow Requirements (EFRs)" to secure enough water for the freshwater ecosystems. In this study, five methods for calculating EFRs were compared to 11 case studies of locally-calculated EFRs. Three of the methods already existed (Smakhtin, Tennant and Tessmann) and two were developed in this study (the Variable Monthly Flow method and the $Q_{90}\_Q_{50}$ method). The Variable Monthly Flow (VFM) method mimics for the first time the natural flow regimes while being "validated" at global and local scales. The VFM uses 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, over all methods, 37 % of annual discharge was allocated to "Nature" with a higher pressure on low flow requirements (LFR = 46 % to 71 % of average low flows) than on high flow requirements (HFR = 17 % to 45 % of average high flows). Environmental flow methods using fixed annual thresholds such as Tennant, $Q_{90}\_Q_{50}$ and Smakhtin seemed to overestimate EFRs of stable flow regimes and underestimate EFRs of variable flow regimes. VFM and Tessmann methods showed the highest correlation with the locally-calculated EFRs ($R^2 = 0.91$). The main difference between the Tessmann and VFM methods is that Tessmann method does not allow any water withdrawals during the low-flow season. Those five methods were tested within 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. The potentially available discharge for human use lies between 12 500 and 15 000 $\mathrm{km^3\,yr^{-1}}$ which represents approximately one third of total available discharge (Rockström and Karlberg, 2010). Despite this large global amount of water, the spatial and temporal uneven distribution can make it locally scarce. Oki and Kanae (2006) indicated that river basins experience severe water scarcity when withdrawals exceed 40 to 60 % of available resources. The global area that faces water scarcity is likely to increase in the future due to continuously-increasing water demands and changes in climate. For example, by 2050, agricultural production is projected to increase by 70 % compared to 2000 in order to secure sufficient food production for 9 billion people (Bruinsma, 2009). This increase in future food production will result in a corresponding increase in water demand and, according to Rockström et al. (2009), about 60 % of the world population could face blue water shortages and 36 % of the world population could face green and blue water shortages. Climate change is also predicted to affect river discharge with decreased low flows and rising river temperatures (van Vliet et al., 2013).

Today, 65 % of continental discharge is considered under moderate to high threat in terms of human water security and biodiversity (Vorosmarty et al., 2010). More than 800 000 dams were built in the last century and 75 % of the main rivers are now fragmented (Richter, 2003). Biemans et al. (2011) show that many rivers are heavily regulated compared to the early 20th century due to increases in water withdrawals and the building of reservoirs especially in South-East Asia, Middle East, coastal US and Australian areas. During the last decade, about half of the river basins have experienced at least one month out of one year of severe water scarcity (Hoekstra and Mekonnen, 2012). Some large river basins, like the Yellow river have even seen their flow reduced by almost 75 % in 30 yr (Changming and Shifeng, 2002) and many rivers do not provide adequate flows anymore to reach their deltas such as the Colorado river or the Nile

(Gleick, 2003). In other river basins such as the Mekong river with its high biodiversity index, flow deviation and dams construction are planned at the possible expense of fish biomass and biodiversity (Ziv et al., 2012).

Compared to terrestrial or marine ecosystems, freshwater ecosystems are more vulnerable (O'Keeffe and Quesne, 2009). Between 1970 and 2000, freshwater ecosystem species have declined by 36 % (Loh et al., 2010). 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). With increasing future water demand for agriculture, industry and human consumption, freshwater ecosystems will therefore be under great pressure.

For the last ten years, a large range of studies have evaluated global water resources and water scarcity with global water models (Arnell, 2004; Alcamo et al., 2007; Rockström et al., 2009; van Beek et al., 2011; Hoff et al., 2010; Hanasaki et al., 2008). These studies highlighted regions with current and future water scarcity. However most of these studies have neglected the water required by the environment or, at best, represented the needs for water very simplistically because there is no global eco-hydrological data available that indicates the level of discharge reduction at which a freshwater ecosystem will degrade. Accordingly EFRs have not been implemented in global water resource assessments at the exception of a few individual global hydrological assessments (Hoekstra and Mekonnen, 2011; Smakhtin et al., 2004; Hanasaki et al., 2008; Gleeson et al., 2012). In individual river studies, the effort to define "environmental flow requirements (EFRs)" such as flow restoration projects (Richter et al., 2006) was significant but there has been no upscaling of individual methods and results. The integration of EFRs into global water models is needed to analyse trade-offs between direct anthropogenic water use (agriculture, hydropower, households and industry) and the water requirements from freshwater ecosystems (which indirectly also serve humans). 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). By ignoring EFRs, the quantity of water available for human consumption globally is probably overestimated (Gerten et al., 2013).

Environmental flow methods should take into consideration the natural variability of river flow in order to maintain and/or restore freshwater ecosystems such as fishes, macrophytes, macroinvertebrates (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). Environmental flows also support freshwater ecosystems through mechanisms such as sediments recruitment and floodplain inundation (Acreman et al., 2008; Bigas, 2012). To ensure protection of all the different aquatic and riverine ecosystems, there is a need for maintaining natural variability of rivers by allocating different flow components for different ecosystems. For example, sustaining a minimal flow is usually important to sustain aquatic ecosystems, while flood flows are usually crucial for the maintenance of wetlands and floodplains (Hugues and Rood, 2003; Bunn and Arthington, 2002). Disrupting a perennial flow can impair aquatic ecosystems and favour proliferation of invasive species and generalist fishes (O'Keeffe, 2009; Marchetti and Moyle, 2001; Poff et al., 2009). Contrary to perennial rivers, flooding a seasonal river during the dry season could disturb the ecosystem such as the invasion of exotic species (O'Keeffe, 2009; Rivers Moore et al., 2007). Freshwater ecosystems in dry areas tend to be more resilient to disturbances than tropical freshwater ecosystems because they are more accustomed to higher variability (Dudgeon et al., 2006; Botter et al., 2013). However, survival of freshwater ecosystems and especially riparian vegetation depends on the maintenance of high flows during the wet season and some days or weeks without flows during the dry season (Doupé and Pettit, 2002).

Global water demands are likely to increase in the future due to a growing population and economic development. Many irrigation projects have been planned without taking into account EFRs (Neumann et al., 2010). By 2050, 100 million km^2 of additional lands are planned to be converted into irrigated lands (Tilman et al., 2001). Therefore, it is necessary to know where along river courses water will be available for future agricultural expansion without compromising EFRs.

To be able to assess where enough water will be available for withdrawals for expanding irrigated areas and other uses, it is necessary to estimate how much water is needed to sustain freshwater ecosystems. The aim of this study is to compare different methods of EFRs calculation and their applicability for global water assessments. That way, the limits on sustainable water withdrawals for other water users can be better defined. In this paper, we first present an overview of existing environmental flow methods at local to river basin scale; secondly the different methods are evaluated for implementation globally; and thirdly, based on these analyses, we derived a new method for globally-consistent EPRs assessment. In the final step we applied these five environmental flow methods in a global model. We used the global dynamic water and vegetation model LPJml (Bondeau et al., 2007; Gerten et al., 2004) to simulate natural discharges of river flows and we used 5 methods to calculate EFRs globally and at river basin scale.

2 Review of environmental flow methods

2.1 Legislation of environmental flow methods

While maintaining rivers in good ecological states is a widely acknowledged goal (Richter et al., 2006), existing legislation is not yet generally based on ecohydrological scientific evidence (Richter et al., 2003). Today, only a small fraction of rivers around the globe are being controlled by any environmental flow legislation (Richter et al., 2011). Many countries of the developed world have implemented water acts in order to protect freshwater ecosystems such as the federal Clean Water Act in the US (Adler et al., 1993) and the New South Wales Water Management Act 2000 in Australia (Kingsford and Auld, 2005) but also the pioneering African Water Act of 1998 in South Africa (Hugues and Rood, 2003), assessing the ecological states of their rivers and elaborating environmental flow methods such as BBM, Tennant etc. (see Sect. 2.2). In Europe, the European Water Framework Directive (WFD; 2000/60/EC) requires good ecological conditions for all water bodies by 2015. European rivers were classified into five categories among which 50 % of the rivers were classified in a category below the "good ecological status" (Agency, 2012; Borja et al., 2006; Fernández et al., 2012). Today, only a few studies have quantified EFRs at European level and most of the time by only allocating a minimal annual flow threshold (Palau, 2006). In the developing world, environmental flow requirements are even less part of legislation and only few studies have been carried out on the ecohydrological status of regulated rivers (Benetti et al., 2004).

2.2 Review of environmental flow methods

Today, more than 200 environmental flow methods exist and they are classified into four classes: hydrological methods, hydraulic rating methodologies, habitat simulation methodologies, and holistic methodologies (Tharme, 2003). Most environmental flow 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). Examples of the different EFRs methods used in local studies are found in Table 1, whereas, global EFRs methods are mainly based on hydrological methods due to a lack of global ecohydrological data (Richter et al., 2006), at the exception of Xenopoulos et al. (2005) who related global fish species richness with river discharge.

2.2.1 Hydrological methods

Hydrological methods are usually using fixed annual low 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). Other methods such as the Tennant method (Tennant, 1976) determines first the level of ecological degradation of a river among seven classes going from “severe degradation” (F) to “outstanding” ecological conditions (A). According to this classification, a percentage of the mean annual discharge is allocated during wet (high flow) and dry (low flow) seasons. The Tessmann method (1980) considers intra-annual variability by allocating percentages of monthly flow for EFRs depending on the different flow seasons (high, intermediate or low). Richter et al. (1997) grouped Indicators of Hydrological Alteration (IHA) into five groups: magnitude, timing, duration, frequency and rate of change. Environmental flow components (EFCs) were later included to the IHA software in order to prescribe some flow standards such as maintenance flows (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 monthly mean flow (± standard deviation) in parametric analyses (Smakhtin et al., 2006; Yasi et al., 2012; Richter et al., 2012). The advantage of hydrological methods is that they are simple and fast to use in preliminary assessments or when ecological datasets are not available. They can be implemented at local and global scale depending on their level of complexity.

2.2.2 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 inconvenient of this method is that it requires river hydraulic measurements and is specific to each river section.

2.2.3 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 development (Palau and Alcázar, 2010; Jowett, 1989). The advantage of habitat simulation models is that they take into consideration riverine ecosystem but data collection may be an economic and a time constraint. Habitat simulation models also need calibration when they are applied to a different region and are usually specific to one fish species (McManamay et al., 2013; Orth et al., 2013).

2.2.4 Holistic methods

Holistic methods are a combination of hydrological, hydraulic, habitat simulation methods and expert knowledge and are increasingly used (Shafroth et al., 2009; Poff et al., 2009). The Building Block Model (BBM) is a well-documented method to estimate environmental flow requirements at local or basin scale (King and Louw, 1998; King and Brown, 2010; Tharme, 2003; Hugues and Rood, 2003). The building block (BB) method supports the principle that it is fundamental to maintain main 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 BBs 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 and on the flow components (Kashaigili et al., 2007).

DRIFT (Downstream Response to Imposed Flow Transformations) is a model that was developed in a semi-arid region of South Africa where there was little understanding of river ecology. The Lesotho Highlands Water Project developed the DRIFT model, which 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. The second part of the method uses ecohydrological relations to determine EFRs and expert knowledge is included in the last assessment. Holistic methods require large amount of data and time and are difficult to upscale due to the divergence in freshwater ecosystems, flow regime types and water management techniques. The strength of holistic methods is that they promotes inter-disciplinarity where hydrologists, geomorphologists, biologists and sociologists are called to combine their knowledge to find the best compromise between freshwater ecosystem demands and direct human water requirements (Poff et al., 2009).

2.3 Global application of environmental flow requirement methods

Smakhtin et al. (2004) developed the first environmental flow method for global application. In their study, Smakhtin et al. (2004) defined four global 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) determined the global ecological state of rivers as “fair” and Q_{90} was used 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. Smakhtin method is based on annual river discharge and defines EFRs on an annual basis. Hanasaki et al. (2008) developed an environmental flow method considering intra-annual variability based on global monthly river flows. They defined four river regimes: dry, wet, stable and variable and, according to those classes, they determined EFRs as a percentage of mean monthly flow (MMF) depending on the flow regime type (from 10 to 40 % of MMF) and EFRs are based on the ecological status "fair or degrading" of the Tennant method (Hanasaki, personal communication, 2013). Hoekstra and Mekonnen (2012) evaluated monthly environmental flow requirements 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, environmental flow requirements were defined as the monthly flow quantile Q_{90} in the PCR-GLOBWB model (Gleeson et al., 2012).

3 Methods

3.1 Selection of case studies for testing different environmental flow methods

Eleven case studies were selected according to their type of EF methods, flow regimes, locations and Major Habitat Types (MHT). The Major Habitat Types are described in the Freshwater Ecoregions Of the World (FEOW), which classify global rivers into 426 ecoregions (Abell et al., 2008). We chose this classification because it is more robust than a simple global river classification based on climate zones and/or river discharge (Haines et al., 1988; McMahon et al., 2007). It also shows a high divergence of rivers in terms of biodiversity, endemism and river fragmentation. In our selection of 11 case studies, a prerequisite was that each of classes of freshwater ecoregion (xeric, temperate, tropical and polar) should contain at least 2 case studies. Five out six continents should be represented by 1 or 2 case studies. The type of flow regime of the case studies should vary from stable to variable (Table 3). Finally the choice of EF method in the case study should be a habitat simulation model or a holistic model because those methods use eco-hydrological datasets. For example, the Silvan River case study used a habitat simulation model and the Hong Kong case study used a sample of macro-invertebrates to determine optimum and detrimental flow thresholds. However, where ecological datasets are unavailable in the case studies, hydrological methods were tolerated (Table 3), such as the Tanzanian case study, which used a hydrological method (the DRM model approach). The hydrological dataset of individual case studies were obtained from the mean monthly flow of the selected case studies or from the Global Runoff Data Centre (available at http://grdc.bafg.de). Mean monthly flows were calculated with historical datasets of 8 to 30 yr to represent the “natural” conditions of the river. In other cases, such as the Ipswich River in the US and the streamflow of Hong Kong in China, we used a 20 yr average of simulated natural monthly flow between 1960 and 1980 (Sect. 3.3).

3.2 Hydrological indexes

The analyses were all computed over a 40 yr 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).

$$\mathrm{BFI} = \frac{Q_{90}}{\mathrm{MAF}} \tag{1}$$

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

$$\mathrm{HVI} = \frac{(Q_{25} - Q_{75})}{Q_{50}} \tag{2}$$

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 2).

3.3 Selection of global environmental flow methods

As one of the aims of this study was to validate a EF method at global scale and that global ecohydrological assessments are still in their developmental stages (Xenopoulos et al., 2005), the choice EF method was restricted to hydrological methods. In this study, we reviewed, adapted and developed five hydrological environmental flow methods and tested them on the 11 case studies. From that review process, we selected three hydrological methods for calculating EFRs and developed two new methods. The criteria of selection of hydrological methods to be compatible with global hydrological models was that the algorithm defining EFRs should use mean monthly or annual flow values (defined as parametric analyses) or mean annual flow quantile values (defined as non-parametric analyses). We carried out a comparison of different hydrological methods for global application. To do so, five hydrological environmental flow methods were applied on 11 case studies in order to compare the results with those of locally-calculated EFRs. The allocation of EFRs depends on the ecological status of a specific river and is usually defined by stakeholders in river basin projects and, in most of the cases, it is unlikely that the pristine state can be rehabilitated (Table 3). For the global application, we defined the ecological status of rivers as in “fair” conditions. Only in the case of the Tennant method we defined the global ecological status of river to be “good” as the algorithm defined for this class defines EFRs as a range going from 20 to 40 % of mean annual flow, and this range is closer to global estimates of EFRs (Smakhtin et al., 2004; Hanasaki et al., 2008) than the algorithm defined for “fair” ecological status. We excluded from our selection environmental flow methods that use daily flows as inputs (e.g. Hanasaki method) because global hydrological models are ,most of the time, validated on a monthly basis (Döll et al., 2003; Werth and Güntner, 2010; Pokhrel et al., 2011; Biemans et al., 2011). Three out of the five selected methods already existed (Tennant, Smakhtin and Tessmann) and temporal scale were adjusted from annual to monthly basis. Two out of the five environmental flow methods were 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 Variable Monthly Flow method). Those 2 methods were developed to increase the sample of global EF methods. We chose to develop a purely non-parametric method ($Q_{90}\_Q_{50}$), which uses flow quantile to allocate minimum instream flow during the high flow and low-flow seasons. We also developed a parametric method (the VMF method), which is based on monthly flow values, takes into account intra-annual variability and ensures water supply for other users during the low-flow season while ensuring at least a minimum instream flow of 30 % of MMF for the "nature" during the whole year. The following methods are described below:

- The Tennant method applied in this study was defined for "good ecological conditions", which allocates 20 % of mean annual flow during the low-flow season and 40 % of mean annual flow during the high-flow season (Table 2).
- The Smakhtin method was applied with the same conditions as in Smakhtin et al. (2004) with a desired "fair" ecological condition (Table 2).
- The Tessmann method was applied according to Table 2. High flows are determined as if mean monthly flow (MMF) is above 40 % of MAF and if 40 % of MMF is above 40 % of MAF, low flows are determined when MMF is below 40 % of MAF and intermediate flows when MMF is above 40 % of MAF and 40 % of MMF is below 40 % of MAF.
- $Q_{90}\_Q_{50}$ was developed for this study based on annual flow quantiles. 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 2).

- The Variable Monthly Flow (VMF) method was developed in this study (Table 2). The VMF method allocates 60 % of the mean monthly flow during the low-flow season (when MMF < 40 % of MAF), 45 % of MMF during intermediate-flow season (when MMF is 40–80 % of MAF) and 30 % during the high-flow season (when MMF > 80 % of MAF). This method follows the natural variability of river discharge by allocating flow on a monthly basis. In extremely dry conditions (MMF < 1 $m^3 s^{-1}$), there is no environmental flow allocation.

In all the EFRs methods except the Variable Monthly Flow method and the Tessmann methods, low-flow season was determined when the mean monthly flow (MMF) was below mean annual flow (MAF) and high-flow season when MMF was above mean annual flow. In two out five methods, intermediate flows were determined in order to make a smooth transition between high flow and low-flow months (Table 2). All global environmental flow methods were applied on a monthly basis to take into account intra-annual variability and favour riverine ecosystems (Gibbins et al., 2001; Poff et al., 2009). The performance of the 5 hydrological methods was tested against the locally-calculated EFRs by using the efficiency coefficient R^2 from Nash and Sutcliffe (1970).

3.4 Description of the global hydrological model LPJml and simulation

The global application and comparison of different environmental flow methods requires the simulation of "pristine" river discharge. For that, we chose the Lund–Potsdam–Jena managed land (LPJml) model 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 global hydrological models 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 yr for carbon and water balance. A simulation was run for naturalized river flow by using exclusively potential natural vegetation (PNV). Environmental flow methods should always be defined based on natural flow from historic datasets otherwise naturalized flow should be simulated. All the analyses were done on a monthly time step. In order to compare EF methods globally, the ratio of monthly EFRs to mean monthly flow was used to show the intra-annual variability of EFRs in space and time. Calculations are shown for two months: January and April. We also compared the annual EFRs of different river basins by giving a range of annual EFRs with the 5 hydrological methods.

4 Results

4.1 Description of the case studies

In eleven case studies, five environmental methods were compared with the locally-calculated EFRs (Table 3–4, Fig. 1). 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 1). They all have relatively stable flow regimes with a strong baseflow index (BFI $\geq$ 20 %) and a hydrological variability index (HVI $<$ 1). Two case studies were selected in the polar

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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 floodplain 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 (comprised between 5 and 15) and the Great Ruaha River is characterised by the strongest variability index (4.3).

4.2 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 mean annual flow (Fig. 1; Table 4). The range of EFRs among the case studies goes from 18 to 63 % of MAF while the range of EFRs among the EF methods goes from 9 to 83 % of MAF. The relative value of low flow requirements on mean annual flow are higher than the relative value of high flow requirements on mean annual flow in half of the cases of which most are variable rivers. On average, low flow requirements represent 46 to 71 % of mean low flows and high flow requirements represent 17 to 45 % of high flows (Table 4). This occurs especially 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 Fig. 2. Among environmental flow methods used, all the simulated EFRs were highly correlated with the locally-calculated EFRs. The Tessmann and Variable Monthly Flow methods recorded the highest coefficient of determination ($R^2 = 0.91$) and Smakhtin, $Q_{90}\_Q_{50}$ and Tennant methods showed a correlation (R^2) ranging from 0.86 to 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 %), and 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 Variable Monthly Flow method was close to the recommended EFRs by about 10 % above average. All the hydrological methods used underestimated EFRs in xeric freshwater ecosystems and overestimated EFRs in polar freshwater ecosystems compared to the locally-calculated EFRs. The methods that were closer to the locally-calculated EFRs for xeric freshwater ecosystems were Tessmann and the Variable Monthly Flow 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 Variable Monthly Flow method (Fig. 1; Table 4).

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 BWR and Iranian cases, 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, Variable Monthly Flow and $Q_{90}\_Q_{50}$ methods were in line with the locally-calculated EFRs of variable rivers, but, only the Variable Monthly Flow and Tessmann methods could capture the intra-annual variability and allocated peak flows during the high-flow season (Table 4 and Fig. 1). 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 EFR methods allocated sufficient water.

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.

4.3 Comparison of environmental flow methods globally

The ratio of global EFRs on the natural flow (PNV) is presented for each environmental flow method on an annual scale (Fig. 3) and on a monthly basis in January and in April (Figs. 4 and 5). Among the methods, EFRs ranged from 25 to 46 % of mean annual flow, with increasing percentage of EFRs from the Smakhtin method to the $Q_{90}\_Q_{50}$ method. On a monthly basis, the Variable Monthly Flow, Tennant and Tessmann methods produced similar spatial patterns of EFRs globally. In January, for example, the North of the Amazon was allocated with more than 60 % of MMF in the case of the Tessmann and VMF methods, whereas in the case of the Smakhtin method, similar quantity of water was allocated in the Amazon River but at different areas compared with the Tessmann and VMF methods. In both cases, 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 whereas in areas characterized by a variable flow, EFRs had a very low to no-flow allocation such as in India (Fig. 3). 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 Variable Monthly Flow 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 globally. The Tennant method calculated high EFRs in the tropics (EFRs $\geq$ 100 % of MMF). However, the Tennant method calculated lower HFRs than the rest of the methods in temperate zones. In those temperate zones, the Tennant method allocated about 20 % of MMF while the Variable Monthly Flow and Tessmann methods allocated at least 40 % of MMF. By comparing Fig. 3 with Figs. 4 and 5, we can see that EFRs look more homogenous on an annual basis than on a monthly basis. The Tessmann method allocated an equal percentage of mean annual flow worldwide and did not show strong differences between regions, whereas, on a monthly basis, the Tessmann method showed clear spatial differences in flow allocation.

In Fig. 6, we compared the five environmental flow methods at the outlet of 14 of the biggest river basins. Perennial river basins such as the Congo, Amazon, Rhine and Mississippi required between 30 to 80 % of MAF and very variable river basins such as the Ganges or the Nile required between 10 to 50 % of MAF depending on the five environmental flow 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 Variable Monthly Flow 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 How are global EF assessments improved ?

This is the first study that compared different hydrological methods for calculating EFRs globally while accounting for intra-annual variability and "validated" those hydrological methods with a set of local case studies. This comparison of hydrological methods was carried out in order to identify methods that could be used in future global water assessment studies. The inclusion of intra-annual variability into the algorithm of the EF method presents a significant improvement compared to previous global water assessments, where the temporal scale was annual (Smakhtin et al., 2004; Vorosmarty et al., 2010). The Variable Monthly Flow (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 case studies containing 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 the usual way of calculating EFRs at global and continental scale which usually uses annual flow thresholds such as low flow indices (Q_{90} or 7Q10) or percentages of MAF (Palau, 2006). The advantage of the Variable Monthly Flow 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 mean annual flow was widely recognized (Hanasaki et al., 2008). Similarly, in the Hong Kong case study, the locally-calculated EFRs for degradation limit was equal to 30 % of mean annual flow and the locally-calculated EFRs for pristine condition was set at 80 % of mean annual flow (Niu and Dudgeon, 2011).

5.2 Differentiation between Tessmann and VMF methods

The main difference between the Variable Monthly Flow and Tessmann methods is that they define high flow, intermediate flow and low-flow seasons with different algorithms and that the Tessmann method allocates higher amount of water: 100 % of mean monthly flow during the low-flow season whereas the Variable Monthly Flow method allocate 60 % of MMF during the low-flow season. The low flow requirements (LFRs) defined in the VMF method are equal to 60 % of MMF because we considered that habitat area for freshwater ecosystems is smaller during the low-flow season than during the high-flow season and thus creates a higher pressure on fish survival compared to high-flow season. Our assumption was 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 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 EF methods based on annual thresholds

The three other methods used either percentages of mean annual flow during the whole year (Tennant) or annual flow quantiles (Smakhtin and $Q_{90}\_Q_{50}$) to allocate EFRs. Those methods tended to allocate too large amount of water during low-flow seasons and too little amount of water during high-flow periods (Fig. 1). As the Tennant method was developed for temperate rivers where intra-annual flow variability is low compared to tropical rivers, the Tennant method overestimated EFRs in variable rivers (including some tropical rivers). The calculated EFRs with the Tennant methods were too low in high-flow season and too high in low-flow season in variable rivers. 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 than with other methods (Figs. 1,3,4, and 5). In variable rivers, the $Q_{90}\_Q_{50}$, Smakhtin and Tennant methods showed a low allocation of EFRs during the high-flow season and a high allocation of EFRs during the low-flow season such as in the Iranian case (Table 4). Similarly, those methods did not seem appropriate for ephemeral and intermittent rivers because they allocated a constant base flow 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 showed to be not flexible as 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 for rivers with better ecological conditions. In fact, monthly EFRs were often higher than the natural average monthly 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 environmental flow 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 (Fig. 1). In addition, in some cases such as the Iranian case, with the locally-calculated EFRs, we can see that only little amount of water is available for other users during the dry season which will probably conflict with irrigation demand. In contrast, the flow of the Chilean case study is constant for the whole year such as the locally-calculated EFRs. The Tessmann and the Variable Monthly Flow methods performed well with defining EFRs of different flow regimes because the allocated flow is based on the average monthly flow and not on annual flows.

5.5 Monitoring and systematisation of future EFR studies

Environmental flow methods are still at an early stage. Consequently, environmental flow requirements 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 not of 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 multidisciplinary methods (Poff et al., 2009; Pahl-Wostl et al., 2013).

5.6 Limitations of our study

The choice of environmental flow 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 environmental flow methods across a set of existing case studies located in different climates and freshwater ecosystems regions. Amongst the 200 existing environmental flow 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 instance, 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 yr, 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 able to account for daily high and low flood pulses, which often drive riparian vegetation (Shafroth et al., 2009).

5.7 Refining global water assessments

Given the lack of global datasets on riverine ecosystems and river hydraulics, the use of the VMF method is recommended for global application over any other method using a fixed annual flow threshold. However, we recommend to use a more applied method such as a habitat simulation model over the 5 EF methods for local applicability when data is available. This study did not aim at refining locally-determined environmental flow methods but at identifying one or several methods for global application. Thanks to these new estimates of EFRs, improved global water availability assessments can better inform other water users and 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 Variable Monthly Flow 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 worth noticing 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 Fig. 6 a range of annual EFRs at a river basin scale by using the five hydrological environmental flow methods. The Variable Monthly Flow method is always within the range of the five hydrological methods compared with methods such as Q_{90}_Q_{50} which can underestimate LFRs and overestimates HFRs. However, EFRs are also changing intra-annually variability (data not shown).

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).

5.8 To be considered in future EF assessments

In future global EF assessments, it is important to consider the inter-annual variability of flow regimes as EFRs are most of the time calculated on a long period average (> 20 yr) such as in Hessari et al. (2012), where EFRs were calculated for both average year and dry year. 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 Conclusions

We tested five different hydrological environmental flow methods for their applicability in global water assessments and found the Variable Monthly Flow Method to be a valid and easy method for implementation in global hydrological models due to its simple algorithm, which also takes into account intra-annual variability. It improves environmental flow calculations, thanks to its increased time resolution from an annual to a monthly basis and due to its global applicability. The Variable Monthly Flow method was validated with existing EFR calculations from local case studies and showed good correlations with these. 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 EFR method	Data input	Example	Sources
Hydrological	Long-term dataset of unregulated or naturalized daily flows	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 tested hydrological EFRs methods with MAF the Mean Annual Flow, MMF the Mean Monthly Flow, Q_{90} the 90th quantile of a river discharge on an annual base or the flow exceeded 90 % of the period of record and Q_{50} the 50th quantile of a river discharge on an annual base or the flow exceeded 50 % of the period of record.

Hydrological season	Smakthin (2004)[b]	Tessman (1980)[c]	Tennant (1976)[b]	$Q_{90}\_Q_{50}$ (2013)[b]	Variable Monthly Flow (2013)[d]
Low flows (LFRs)	Q_{90}	100 % MMF	20 % MAF	Q_{90}	60 % MMF
High flows (HFRs)	0 to 20 % MAF[a]	40 % MMF	40 % MAF	Q_{50}	30 % MMF
Intermediate flows (IFR)		40 % MAF			45 % MMF

[a] If $Q_{90} > 30\,\%$ of MAF, HFRs = 0, if $Q_{90} \leq 30\,\%$ of MAF and $Q_{90} > 20\,\%$ of MAF, HF = 7 % of MAF, if $Q_{90} \leq 20\,\%$ and $Q_{90} > 10\,\%$ of MAF, HF = 15 % of MAF, if $Q_{90} \leq 10\,\%$, HF = 10 % of MAF.

[b] High flows are determined as if MMF ≤ MAR and low flows are determined as if MMF > MAR.

[c] High flows are determined as if mean monthly flow (MMF) is above 40 % of MAF and if 40 % of MMF is above 40 % of MAF, low flows are determined when MMF is below 40 % of MAF and intermediate flow requirements (IFRs) when MMF is above 40 % of MAF and 40 % of MMF is below 40 % of MAF.

[d] High flows are determined as if MMF is above 80 % of MAF, intermediate flows as if MMF is between 40 % and 80 % of MAF, and low flows as if MMF is below 40 % of MAF.

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

Case study	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
Urmia lake 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 sub-trop coastal river	1. RVA approach (Q_{25}–Q_{75})	133.5 (49.4–251.3)	15.4	1.7	5	1	6
Great Ruaha river, Tanzania (Kashaigili et al., 2007)	Tropical and sub-trop 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 ($m^3 s^{-1}$)
[3] LF: Low flow average calculated as the average flow when MMF > MAF ($m^3 s^{-1}$)
[4] HF: high flow average calculated as the average flow when MMF ≤ MAF ($m^3 s^{-1}$)
[5] Baseflow index: Q_{90}/MAF (see Eq. 1)
[6] Hydrological variability index: $(Q_{25}–Q_{75})/Q_{50}$ (see Eq. 2).

Table 4. 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)	Smakthin (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)
Urmia lake 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, Jansson 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 sub-trop 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 sub-trop 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)

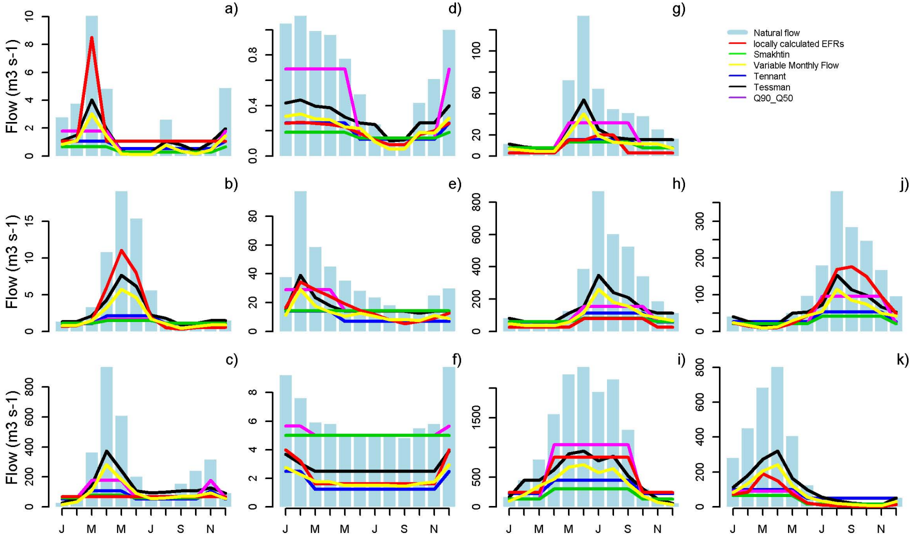

Fig. 1. Comparison of EFR methods with locally-calculated EFRs in different case studies **(a)** BWR, US, **(b)** Urmia dam, Iran **(c)** Ipswhich river, US, **(d)** Silvan river, Spain, **(e)** Osborne dam, Zimbabwe **(f)** Huasco river, Chile **(g)** Voijm dam, Sweden, **(h)** Newhalen river, Alaska, **(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.

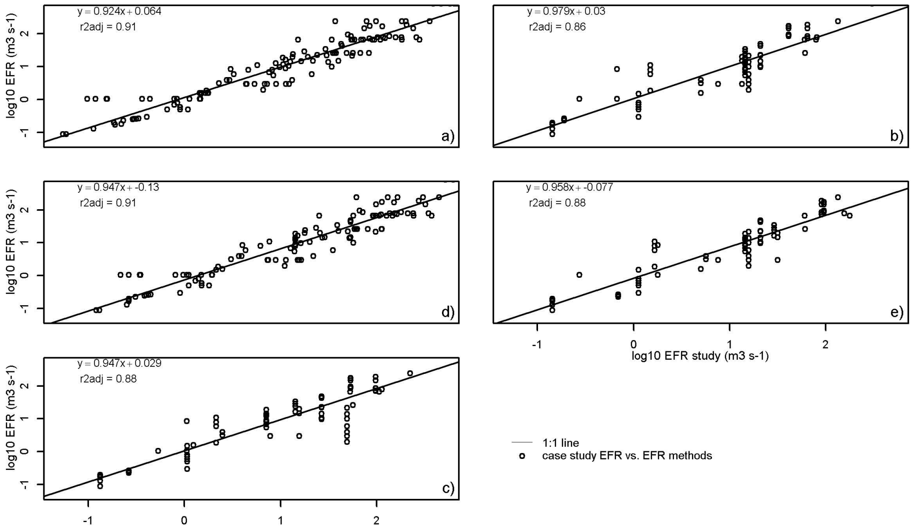

Fig. 2. Validation of five environmental flow methods with the locally-calculated EFRs of 11 case studies with **(a)** Variable Monthly Flow, **(b)** Smakhtin, **(c)** Tessmann, **(d)** Q_{90}_Q_{50}, **(e)** Tennant.

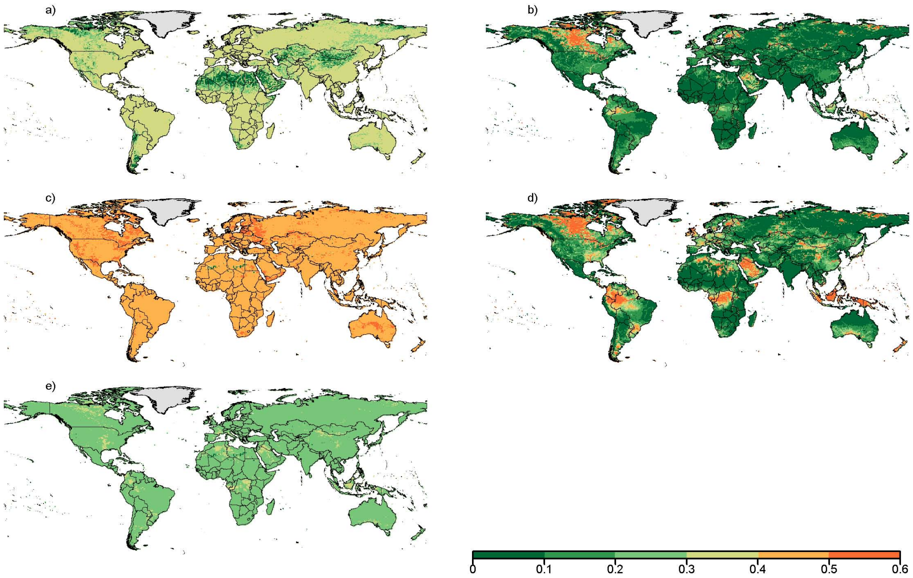

Fig. 3. Ratios of annual environmental flow by annual natural flow within **(a)** Variable Monthly Flow, **(b)** Smakhtin, **(c)** Tessmann, **(d)** $Q_{90}\_Q_{50}$, **(e)** Tennant environmental flow methods.

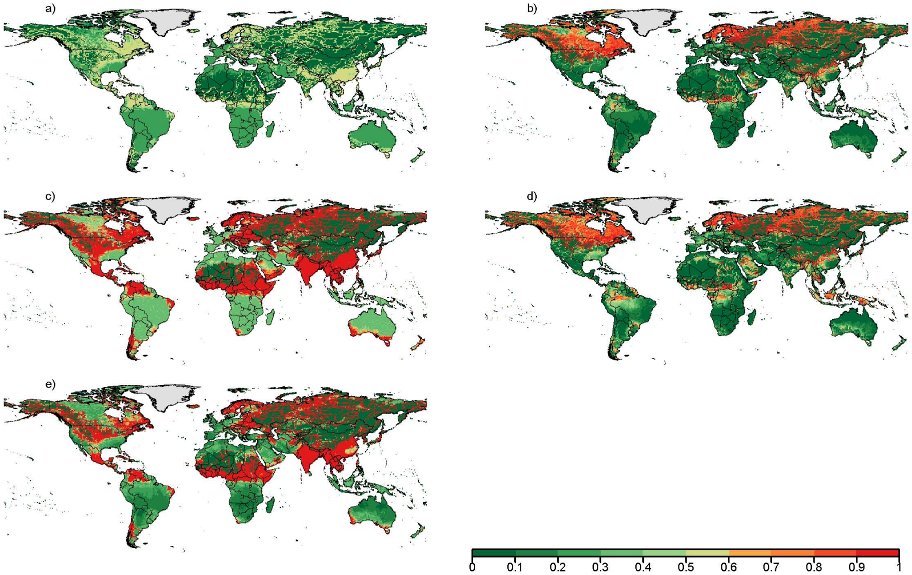

Fig. 4. Ratios of monthly environmental flow by monthly actual flow (January) within **(a)** Variable Monthly Flow, **(b)** Smakhtin, **(c)** Tessmann, **(d)** $Q_{90}\_Q_{50}$, **(e)** Tennant environmental flow methods.

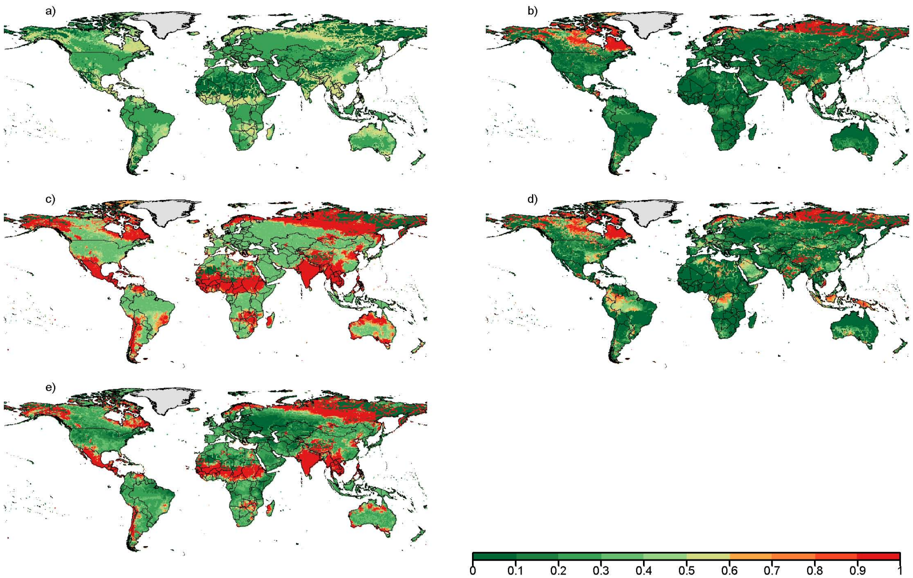

Fig. 5. Ratios of monthly environmental flow by monthly actual flow (April) within **(a)** Variable Monthly Flow, **(b)** Smakhtin, **(c)** Tessmann, **(d)** $Q_{90}\_Q_{50}$, **(e)** Tennant environmental flow methods.

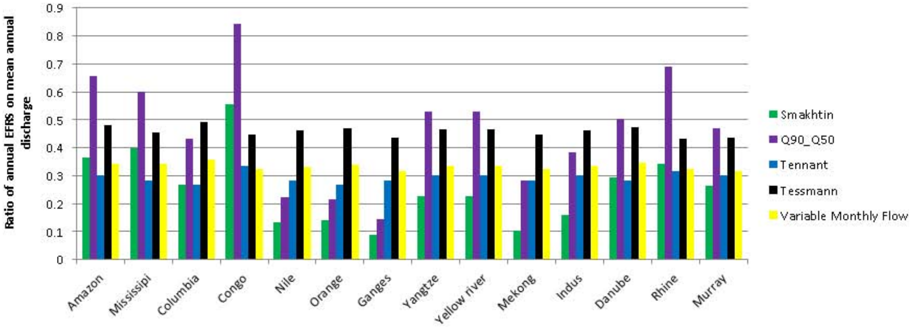

Fig. 6. Comparison of 5 environmental flow methods at the outlet of 14 river basins.

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