Response to Referee #1

We would like to express our gratitude for the comments, critics, and suggestions that will help us to improve our manuscript to Referee 1. Our responses (in blue) are provided here together with the original comments (in black).

While the research design presented is reasonable, the presentation is very poor. This includes the structure of the text, the description of methods and data, the analysis of the data and the use of the English language.

In our reply to referees, we have included:

- a table giving a detailed description of the different environmental flow methods (Table 1),

- a table with detailed explanation of the localization and the hydrological datasets of the study cases (Table 2),

- a new figure showing the localization of the study cases in the Freshwater Ecoregion Of the World (FEOW) map (Figure 1).

We have also changed the text/analysis as suggested (see below for specifics; Figure 2).

In the revised version we will give a more detailed description of the different environmental flow methods and we will have our manuscript checked for the use of the English language.

In addition, the framing of the research is insufficient; the lack of actual information of the effect of river discharge alterations on freshwater-dependent biota,

In the revised manuscript we will include in the introduction how difficult it is to quantify the impact of river discharge alteration on freshwater-dependant biota (Poff and Zimmerman, 2010). We will explain that eco-hydrological relationships are already difficult to obtain at local scales so it is nearly impossible to do that at global scale. In the revised introduction, we will clarify the purpose of developing a new global environmental flow model: "*In the current global water resources assessments, water for nature and/or environmental flows is almost always neglected or included in a very simplified way. We aimed to develop a method which can be used in global water assessments to set a limit to water extraction for irrigation and other human water users and/or to show regions where conflicts between water for nature and water for other users occur*". Water availability is even sometimes neglected in global assessment of impact of climate change and land-use change and here we would like to emphasize the need to include water availability in global assessments but also a quantification of EFRs. This will result in an improved quantification of water availability for sustainable water extraction for irrigation purpose. However, we do acknowledge that our methods are far from perfect and do not aim at representing a perfect relation between flow alteration and its impact on freshwater dependent biota. Therefore, we recommend to use holistic EF methods in regional analyses such as the ELOHA method. In this study, we have "validated" a simple method with local study cases located in different freshwater ecoregions (Figure 1) to be able to set a limit to water extraction at global scale in the absence of international EF legislation.

as well as the fact that EFRs are societal decisions, is not reflected.

We fully agree with the reviewer that in the end EFRs are a societal decision which is often made a local scales and quantification of EFRs depends on the level of protection that is desirable by society/policy. However to develop a 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’. Including societal decisions in these models is at the moment very difficult and is beyond the aim of our paper but we will include a detailed explanation of the study from Pahl-Wostl et al. (2013) for societal issues who suggest that a "*more systematic approach to EFR analysis on both the natural and social science fronts and a unifying framework for the assessment and implementation of sustainable EFRs in national water policy, in IWRM plans for river basins, and in global environmental water assessments are part of a new research agenda proposed for global change science*".

At the moment, we cannot possibly address this full new research agenda but we limited ourselves to a the quantification of EFRs as a function of biophysical parameters.

Specific comments

Abstract

It is not correct to say (or at least not meaningful) that the “VMF method mimics for the first time” natural flow regimes:”. The Tessmann method also seems to do this (even though the explanation of the method in section 3.3. and Table 2 is not clear), and so does the “presumptive standard for environmental flow protection” of Richter et al. (2012) which would allocate 80% of mean monthly flows to the environment . It was cited in the literature review in 2.2.1 but not further discussed later.

We reviewed the sentence “VMF method mimics for the first time” and acknowledged the comments of the reviewer by changing it to: “*For the first time, five hydrological EF methods including the new “Variable Monthly Flow” (VMF) method were compared and “validated” at global and local scales by including intra-annual variability of the natural flow regime*”. In a context where water withdrawals were usually prioritized over environmental flows, we consider that the VMF method could be applicable for the achievement of “*fair ecological conditions*”. The VMF method allows water depletion from 40 to 70% of the mean monthly flow while the Tessmann method allows water depletion up to 60% of MMF (and no water extraction during dry season).

We have reviewed the “*presumptive standard for environment flow protection*” which only allows 20% of MMF depletion and we would like to clarify that this method was defined with desired achievement of “*good ecological conditions*” with four study cases (Richter et al., 2012). Therefore, we specified in the text: “*We also excluded the Hoekstra et al. (2012) method because they defined EFRs to achieve good ecological conditions and we defined our ecological conditions to “fair ecological conditions”.*” Moreover, the VMF method such as the Tessmann methods use different percentage of flow per month depending on the flow season (dry/wet season) while the Hoekstra method does not.

1 Introduction

The introduction is too broad and does not guide the reader well to work presented later. For example, the first paragraph is, in my opinion, superfluous.

In a revised manuscript, we will reframe the introduction (including 1st paragraph) and discuss the difficulties and uncertainties of how difficult it is to determine EFRs at any spatial scale. We will include a comment on the difficulties to relate freshwater-ecosystem responses to flow alteration (see below) and we will also reframe the objective of our study: “*In this study, different EF methods were* *tested and compared at different temporal and spatial scales with the aim to restrict future unsustainable water withdrawals at global scale.*"

On the other hand, important information on the poor degree of scientific knowledge about the effect of flow alterations on freshwater ecosystems is not presented (e.g. Poff, N. L. and Zimmerman, J. K. H.: Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows, Freshwater Biol., 55, 194– 205, 2010). This would be required for the reader to understand how extremely uncertain any quantification of EFRs to achieve a "fair" or "good" status of the ecosystem is.

In the revised manuscript, the introduction we will contain a paragraph explaining the limited knowledge and difficulty in defining quantified EFRs by also referring to the suggested journal article from Poff and Zimmerman (2010).

2 and 2.2 have the same title.

We will remove the paragraph 2.1 on legislation of environmental flows and start with the "Review of environmental flows".

The Xenopoulos et al. (2005) study does not deal with EFRs but quantifies the effect of mean river discharge on fish species number.

We will rephrase section 2.2 such as:

"*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 is difficult to relate freshwater biodiversity with flow metrics at local and global scale (Poff and Zimmerman, 2010).*"

2.1 There is no "legislation of environmental flow methods"; what is described here relates to legislation regarding environmental flows. The scope of the European WFD is incorrect or at least misleading, as good ecological status does not (directly) relate to EFRs. The section should be deleted (or rewritten and moved to the introduction.

We agree with the reviewer and deleted section 2.1 from the manuscript and we leave societal and legislation issues of EFRs to be addressed in other journal articles (see comments in above sections).

3.1: It is not well explained which flow data were used to compute the five EFR values for each case study. In particular, how well are "natural" conditions represented in each case study=

In the new version of the manuscript we will add a new table explaining how flow data were obtained or simulated (see Table 2 below).

3.3 and Table 2. A clearer description of the five EFR methods is required, and a description of the rationale of each methods. E.g. in Table 2, the explanations in superscripts are not well formulate or are even wrong (b).

We revised section 3.3 and included a table to describe the 5 methods (see Table 1 below) with detailed description on:

- how high, intermediate and low flows are determined in each method

- the description of each EF algorithm per method and per flow season

We will also explain that methods such as Tennant, Smakhtin and Q50_Q50 were adjusted from annual to monthly time step because there was not existing literature of how those methods could be applied on a monthly time step. For that, we defined two important flow seasons: high-flow and low-flow seasons. We also clarified in table 1 how high/intermediate/low flow season are defined.

4.2 Not meaningful to correlate EFR of case studies to computed EFRs in absolute numbers, as you did in Figure 2, better to do it, as in Table 4, normalized. Absolute numbers of EFR vary by a factor of 1000, which is a much higher number than the ratio of mean annual flow to EFR! In addition, it seems inconsistent that in three out of the five methods (b,c,e), one case study EFR is related to many computed values. E.g. in the Smakhtin method, only eleven points altogether should be shown. Is this maybe the reason for the lower R2 of these three approaches?

Table 3: Not clear how the number of high/intermediate/low flow months are defined (Tessmann of FVM), and why intermediate months and in Table 4 only low and high flow requirements mentioned?

We would like to clarify that in Figure 2, data (mean monthly EFR) were normalized by using log10 because, as the reviewer shows, results vary by a factor of 1000 in absolute numbers. With the log10 transformation, the values are limited to a range between -1 and 2 (see Figure 2 below).

We would also like to clarify also that each study case has 12 mean monthly EFR values (for 12 months). Therefore, for each EF method, we count 11 study cases *12 monthly values per EF method for Fig.2 a, b, c, d and e.

To acknowledge this comment, we changed the legend for Figure 2 from "*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) Q90_Q50, (e) Tennant*" to "*Relation between the calculated EFRs with the locally-calculated monthly EFRs of 11 study cases with (a) Variable Monthly Flow, (b) Smakhtin, (c) Tessmann, (d) Q90_Q50, (e) Tennant. In each sub-figure, each dot represents an EFR for one month and for one case study.*"

In Table 1, we explained how low/intermediate/high flows were defined and usually intermediate months only accounted for 1 or 2 months out of 12 months. Therefore, to be able to compare the 5 EF methods on an annual basis for the analyses of Table 3 and 4 of the manuscript, we defined 2 seasons (high and low flow months) for each of the 5 EF methods (low flow months are defined when mean monthly flow is below mean annual flow and high flow months when mean monthly flow is above mean annual flow).

5.1. Hoekstra and Mekonnen (2011) (HOEKSTRA, A.Y. & MEKONNEN, M.M. (2011): Global water scarcity: monthly blue water footprint compared to blue water availability for the world's major river basins, Value of Water Research Report Series No. 53, UNESCO-IHE, Delft, Netherlands) already considered interannual variability of EFR in their global-scale water scarcity study.

First, we think that the reviewer aimed to write *"...considered intra-annual variability.."* instead of "*...considered inter-annual variability*.." because none of the studies mentioned including our study rose the issue of inter-annual annual variability except in our study in the discussion sections 5.6 and 5.8. At this stage, the only way to tackle inter-annual variability was to define EFRs on long-term hydrological database (at least 15 years) to account for dry and wet years.

Second, it is true that Hoekstra et al. (2012) already used "*the presumptive standard for environmental assumption*" a method using percentage of monthly flow and we have neglected to explain why we do not use it in our study. First, Hoekstra and Mekonnen (2011) allocate the same percentage of flow during the year (80% of MMF) so they do not differentiate between high/low months, second, they used 80% of mean monthly flow and validated the percentage of flow with 4 study cases with desired "*good/outstanding*" ecological conditions (Richter et al., 2012) while we aim at "*fair*" ecological conditions and we validated our methods with 11 study cases spread in different continents and freshwater ecoregions (see Figure 1 below). Finally, we think that restricting water extraction to only 20% of monthly flow would not be realistic in many regions. For example, in the Mediterranean and in south-east Asia current surface water extraction is already above 75% of monthly flow.

To acknowledge this, in the revised manuscript we will change part of our abstract, we will explain in the selection of EF methods why we did not select the method from Hoekstra et al. (2012).

5.3. It is incorrect to say that Tennant, Smakhtin and Q90_Q50 method allocate too large amounts of water during low-flow seasons etc. At least Smakhtin et al. only deal with total annual EFR such that also the representation in Figure 1 is incorrect, and the discussion at the end of 5.3 is not meaningful.

We agree with the reviewer that it is not correct to use "*too low or too large amount of water*". We will clarify this in the revised manuscript by only comparing the amount of water the different methods allocate to EF.

We would also like to clarify why and how the Smakhtin and Tennant methods were adjusted in our study. To be able to define how much water is available for irrigation or other users, it is essential to define EFRs at shorter timescales than annual timescales because irrigation is always planned on sub-daily, daily or monthly time-step. So, to make those methods applicable at monthly time scale and be reliable when compared to monthly irrigation requirements, there are two options:

1. To divide the total annual environmental flow requirements volume into 12 equal values (representing the EFR volume per month).
2. Or to take into account intra-annual variability and develop a simple rule dividing the river hydrograph into low/high flow months. Thus, for Smakhtin, Tennant, Q90_Q50 methods, we separated annual flow into high/low flow season (see Table 2 below) and allocate a different percentage of mean annual flow according to the flow season. For example, the Smakhtin method did not refer of how EFRs were allocated during the year, thus, we made the assumption that base flow (here flow quantile Q90) was allocated during the low-flow season and the flow quantile (Q90) + a percentage of mean annual flow (0-20% MAF) was allocated during the high-flow season.

In our paper we selected option 2 because we think that option 2 was an improved representation of EFRs compared to option 1 and we wanted to include intra-annual variability with an emphasize on different flow seasons (high and low-flow periods). In an improved manuscript, we will clarify how methods were adjusted.

Finally the explanation 5.3 will be reformulated as such: *"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 (see Figure 1 of the manuscript). Hence using higher annual flow quantiles (paragraph 5.3) such as Q50 and Q75 (Smakhtin et al., 2004) does not improve the quantification of EFRs and using a parametric EF* *method such as a percentage of flow is more appropriate than non-parametric methods such as flow quantiles."*

5.4. (Sentence on p. 15009, l. 18). Given the underestimation of EFR in xeric basins and the low fit in polar ones (Table 4) of the VFM, it is not correct to write this sentence.

We will change the sentence (p. 15009, l. 18) into: *"The Tessmann and the Variable Monthly Flow methods performed better than methods using annual thresholds because temporal representation of EFRs was defined with a parametric monthly time-step algorithm. However the quantification of EFRs of xeric freshwater ecosystems and polar freshwater ecoregions is still difficult to define compared to the quantifications of EFRs of temperate flow regimes.* "

Response to Referee #2

We would like to express our gratitude for the comments, critics, and suggestions that will help us to improve our manuscript to Referee 2. Our responses (in blue) are provided here together with the original comments (in black).

General comments: - The paper clearly states the questions that the authors seek to address. - The authors show familiarity with literature on setting environmental flows. Major papers and schools of thought appear to be accurately summarized and referenced. - There is a lot presented in this paper: (a) comparison of five hydrologic methods with local methods for determining EFRs; (b) comparison of environmental flow methods applied globally (presented in Figs 3-5); (c) application to 14 global river basins (presented in Fig 6). - The bulk of the paper is on (a), and the related methods, results, discussion and conclusions are pretty well presented and explained. In comparison, (b) and (c) receive almost cursory treatment and may be better presented as separate papers - expanding on them here would likely be too much to digest in one paper. I could follow (a) to its conclusion about advantages/disadvantages of the five hydrologic methods and whether they EFRs are high/low relative to each other and in different major habitat types, which will be useful context for understanding both global and local applications of these five methods. In contrast, there was relatively little discussion and few conclusions to take away from the analyses in (b) and (c) . They seem almost as an afterthought.

We agree with the reviewer that the focus of the paper is on part (a). However, we are of the opinion that part (b) and (c) are essential part of our paper and we would like to clarify and justify why parts (b) and (c) were included. Comparing and "validating" EF methods at local scales (a) was done to be implemented in global water assessment to restrict other water users such as irrigation. Hence, it is important to show how applicable those methods are at global scale by using the global hydrological and vegetation LPJml model (b) and give some preliminary estimates of EFRs at river basin scale (c). Part (b) shows the spatial representation of the 5 EF methods at global scale while part (a) shows the temporal representation of EFRs at local scale and finally part (c) aims at giving a range of EFRs estimates for some large river basins. Part (b) and (c) were included to show how EFRs can be using in future global assessment of land-use and climate change. In the revised version of the paper we will better explain why part (b) and (c) were included.

Specific comments:

- Page 14989, line 15: The terms 'green' and 'blue' water may not be familiar to all readers. To clarify the point, which is important, consider replacing these terms with a description of these two components of the water cycle.

As suggested by the reviewer, we would like to clarify the term "green water" by the amount of water evaporated from plants and soils coming from precipitation and "blue water" as the amount of water evaporated coming from surface waters such as rivers, lakes and reservoirs. As our study is focused on blue water, we will remove the part on green water and will keep the text below: "*about 60 % of the world population could face water shortages coming from blue water (or the part of water coming from surface waters such as rivers, lakes and reservoirs)*".

– Page 15002, lines 15-20: I suggest saying a little bit more about the 'locally-calculated EFRs', perhaps a short paragraph explaining some of the 'environmental flow type methods' used. As written, there is only one sentence referring the reader to Table 3, where the methods are listed in a column. I read past that section without noticing that that was where the local methods were referenced. And since these are the basis for many conclusions about how the global methods perform, the reader deserves a little more information about them.

We acknowledge the comment made by the reviewer and we will extend the paragraph as such: *"In five out eleven study cases, 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 study case was defined with 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 study cases were using EF methods with eco-hydrological relationships such as PHABSIM and RHYHABSIM and the Hong Kong study case which developed an empirical relationship between macroinvertebrates survival and river flow. Finally, one study case used a holistic approach by including expert knowledge (Swedish case study).”* For further details, we refer to the literature review of local EF methods in the section 2.2.

- The comparisons between the global and local methods used to calculate EFRs are pretty well summarized, although in several places the authors make comments that the amount allocated to the environment is ’too large’ (e.g., p 15008, line 14-15). The authors should revise to clarify that the EFRs are ’higher’ or ’lower’ than the local method, and not imply that they are allocating ’too much’ to the environment. The strength of the paper is the comparison of methods - none of which actually estimate how much water these rivers need based on ecological goals. The authors should refrain from concluding that the methods allow ’too much’ or ’too little’ for the environment - such conclusions could only be drawn if they also present presented data on ecological impacts that confirm that EFRs (either local or global) are too conservative or not protective enough. Instead, the authors should use language that emphasizes consistencies and differences among methods.

We agree with the reviewer that the focus of the research is about comparing methods applicable at global scale and we will replace the sentence: *“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).” by *“Compared to methods based on monthly values such as Tessmann and VMF methods, we found that methods based on annual thresholds allocated more water during low-flow season and less water during high-flow season than locally-defined EF methods.”*

Again in page 15008 lines 19-20, we replaced: “*The calculated EFRs with the Tennant methods were too low in high-flow season and too high in low-flow season in variable rivers*.” By “*The calculated EFRs with the Tennant method were lower than the locally-defined EFRs in high-flow season and higher than the locally-calculated EFRs in low-flow season of variable rivers.”*

Table 1. 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
Intermediate flow determination	-	-	-	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 2. Description of geographic coordinates of the study cases and their hydrological datasets

Study cases	Latitude	Longitude	Daily flow data used in study cases	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
Urmia lake, Iran (Yasi et al., 2012)	37.70	45.32	Pre-dam data (1949-2004)	Dataset from the authors

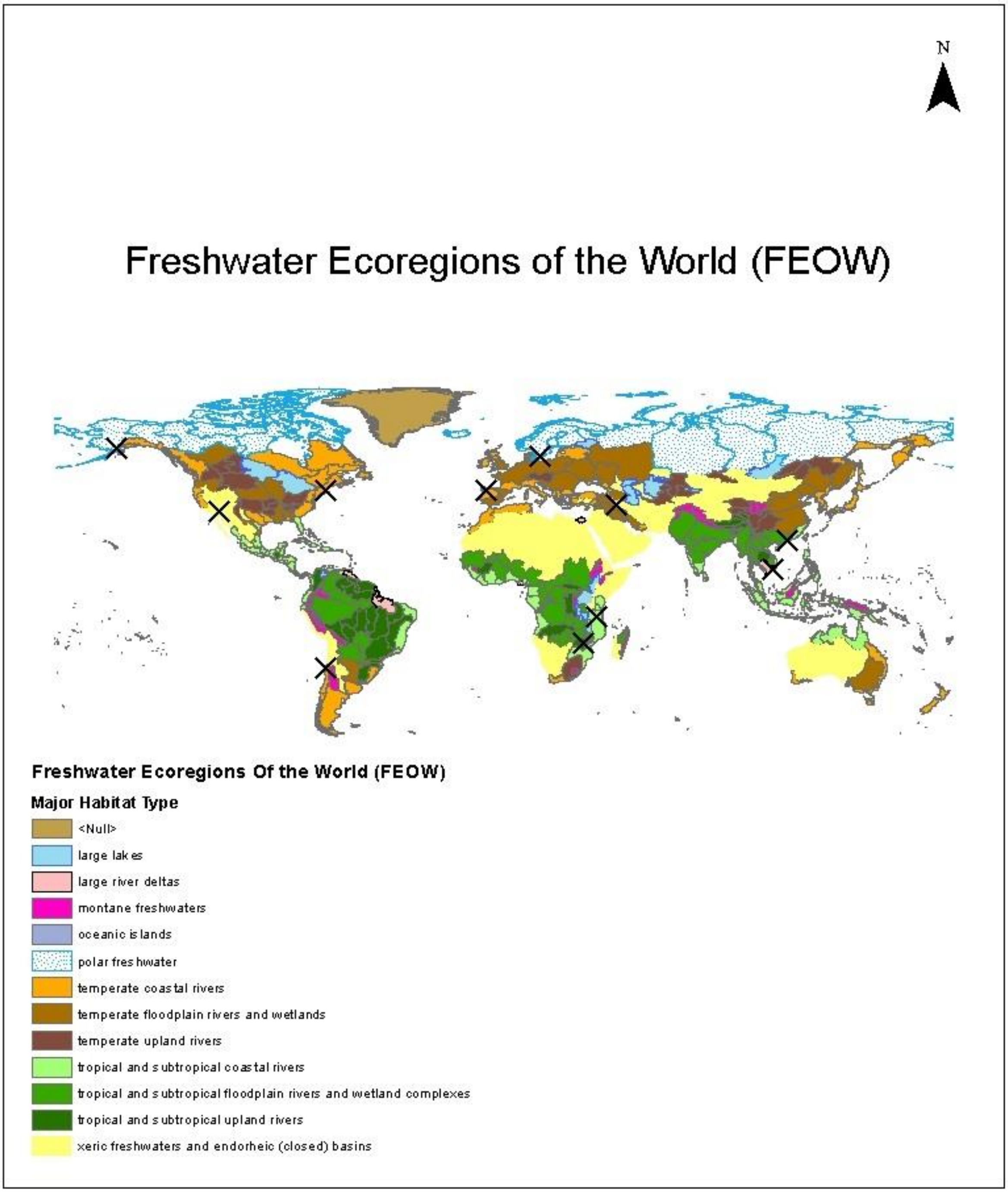

Figure 1. Location of 11 study cases where environmental flow requirments (EFRs) were locally defined.

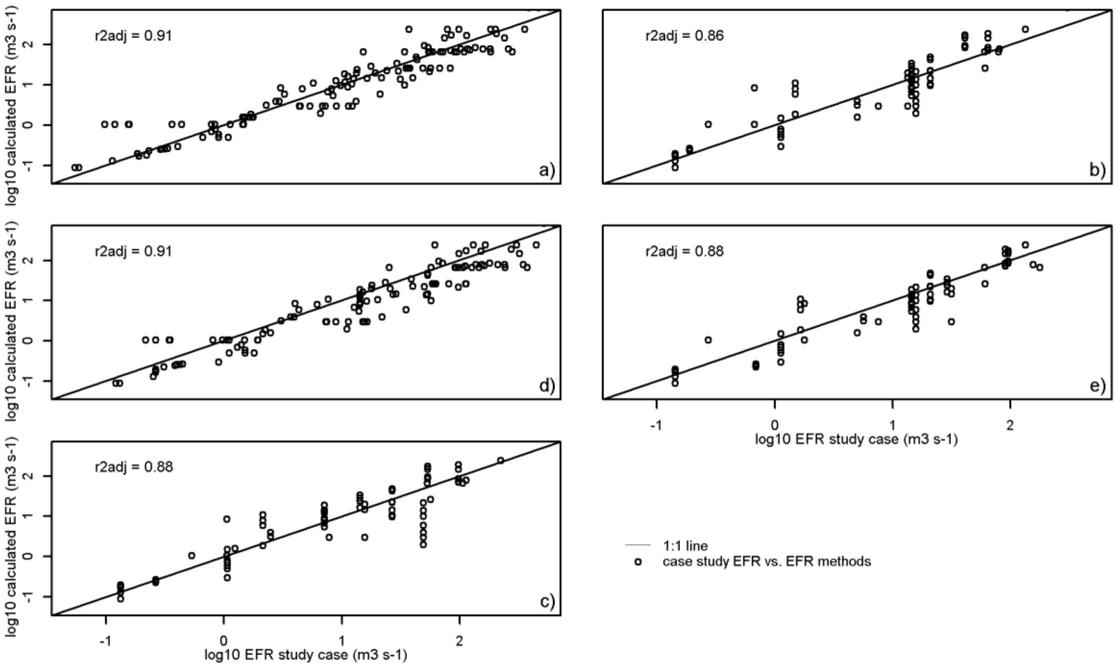

Figure 2. Relation between the monthly calculated EFRs with the locally-calculated monthly EFRs of 11 study cases with (a) Variable Monthly Flow, (b) Smakhtin, (c) Tessmann, (d) Q90_Q50, (e) Tennant methods. In each sub-figure, each dot represents an EFR for one month and for one case study.

Literature

Hoekstra, A. Y., Mekonnen, M. M., Chapagain, A. K., Mathews, R. E., and Richter, B. D.: Global monthly water scarcity: blue water footprints versus blue water availability, PLoS One, 7, 2012.

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