Accounting for environmental flow requirements in global assessments

Amandine Pastor
ESS CALM, Wageningen university

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35 % loss in global freshwater species
(Living planet index report, 2010)
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 (The Brisbane Declaration, 2007).
Environmental flow definition

- High flows for spawning and fish migration
- Floods for channel formation
- Baseflows to maintain habitat in dry season

Loss of intra-annual variability necessary to FE

EFRs = fixed threshold
(Palau et al., 2006)

Adapted from Naiman, 2008
What is done in reality (Palau, 2006)?

By allocating only a minimum base flow we lose the natural variability of the rivers!!!
C) A SPRING-FED RIVER (LESS VARIABLE FLOW)

Natural flows

Environmental flows

ONE YEAR

O’Keefe, 2011
D) A TEMPORARY RIVER (NO FLOW IN THE DRY SEASON)

Natural flows

Environmental flows

FLOW

ONE YEAR

O’Keefe, 2011
1. Overview of methods for flow assessment

Categories of environmental flows methodologies and

1. Hydrologic
   - Tennant
   - $Q_{90}$

2. Hydraulic rating
   - Wetted perimeter method

3. Habitat simulation
   - IFIM
   - PHABSIM

4. Holistic methods

Source: Tharme, 2003
Outline

• How to solve EFRs in global water assessments?
  – What has been done? Smakhtin case
  – Bridging a gap between local and global studies
  – Use of 5 hydrological EF validated with local case studies
  – Implementation in LPJmL (with the aim to define better water availability taking into account EFRs)

• Conclusion (1+2=3)
Defining global ecological states of rivers


<table>
<thead>
<tr>
<th>Conservation status or management objective</th>
<th>Ecological description</th>
<th>Management perspective</th>
<th>Corresponding low-flow characteristic as a measure of LFR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural (unmodified)</td>
<td>Pristine condition or negligible modification of in-stream and riparian habitat</td>
<td>Protected rivers and basins. Reserves and national parks. No water projects (dams, diversions etc.) allowed.</td>
<td>Q50</td>
</tr>
<tr>
<td>Good (slightly or moderately modified)</td>
<td>Largely intact biodiversity and habitats despite water resources development and/or basin modifications.</td>
<td>Minor water supply schemes or irrigation development present and/or allowed.</td>
<td>Q75</td>
</tr>
<tr>
<td>Fair (moderately or considerably modified)</td>
<td>The dynamics of the biota have been disturbed. Some sensitive species are lost and/or reduced in extent. Alien species may occur.</td>
<td>Multiple disturbances associated with the need for socio-economic development, e.g. dams, diversions and transfers, habitat modification and water quality degradation.</td>
<td>Q90</td>
</tr>
<tr>
<td>Poor (critically modified and degraded)</td>
<td>Habitat diversity and availability have declined. Only tolerant species remain. Indigenous species can no longer breed. Alien species have invaded the ecosystem.</td>
<td>High human population density and extensive water resources exploitation. Management intervention is needed to restore flow pattern, river habitats etc. This status is not acceptable from the management perspective.</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Flow regime classification

- **q90 < 0.1MAR**: Less Stable rivers
- **q90 between 0.1MAR and 0.2MAR**: Variable rivers
- **q90 between 0.2MAR and 0.3MAR**: Less Variable rivers
- **q90 > 0.3MAR**: Stable rivers
High flow requirements = $Q_{90} + \%\ MAF$

Low flow requirements = $Q_{90}$
Figure 2. A global distribution of estimated total EWR, which would be required to maintain the freshwater-dependent ecosystems in fair condition.

The global picture of EWR (Figure 2) effectively reflects the hydro-ecological assumption formulated by Hughes and Hannart (2003). In highly variable flow regimes, the aquatic life is used to the extended periods of low flow. Some regions are characterized by a long-term water scarcity, and as a result of this process, they form great river basins and other drainage regions, which cover the entire land surface (their boundaries are shown in Figure 3). These basins and regions have been used by Cai and Rosegrant (2002) and Rosegrant and Cai (2002) for modeling the water demands.
High flow period

Low flow period

River flow

Environmental flows

Irrigation demand

Environmental flows

Irrigation demand
Outline

• Problem (1): how to solve EFRs at global scale?
  – What has been done? Smakhtin case
  – Which EF methods to use?
  – Use of 5 hydrological EF validated with local case studies
    – Implementation in LPJml (with the aim to define better water availability taking into account EFRs)

• Conclusion (1+2=3)
Bridging a gap between local and global knowledge

• No existing global hydro-ecological database = at global scale, we use hydrological EF methods

• But...

• We choose case studies belonging to diverse freshwater ecoregion (FEOW) (WWF, 2009)
EFR case studies from different freshwater ecoregions
<table>
<thead>
<tr>
<th>Study cases</th>
<th>Major Habitat Type</th>
<th>Classification: 1. Ephemeral, 2. Intermittent, 3. Perennial</th>
<th>Mean annual flow (m3.s⁻¹)</th>
<th>Q90/MAF (%)</th>
<th>CV (3 driest months/MAF)</th>
<th>Average EFR results (average LFR-average HFR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bill William river, US (Shafroth, Wilcox et al. 2009)</td>
<td>Xeric freshwater</td>
<td>1</td>
<td>2.7</td>
<td>5.3</td>
<td>0.10</td>
<td>46 (48-26)</td>
</tr>
<tr>
<td>Sharh Chai river, Yasi et al. 2012</td>
<td>Xeric freshwater</td>
<td>1</td>
<td>5.3</td>
<td>21.1</td>
<td>0.22</td>
<td>33 (66-28)</td>
</tr>
<tr>
<td>Ipswich river, US (Armstrong D.S., Todd A. et al. 1999)</td>
<td>Temperate coastal river</td>
<td>2</td>
<td>265.0</td>
<td>22.6</td>
<td>0.21</td>
<td>33 (46-17)</td>
</tr>
<tr>
<td>Silvan river, Spain (Palau and Alcázar 2010)</td>
<td>Temperate coastal river</td>
<td>3</td>
<td>0.7</td>
<td>21.5</td>
<td>0.25</td>
<td>43 (63-37)</td>
</tr>
<tr>
<td>Zimbabwe (Symphorian, Madamombe et al. 2003)</td>
<td>Temperate coastal river</td>
<td>3</td>
<td>39.7</td>
<td>43.6</td>
<td>0.38</td>
<td>44 (62-29)</td>
</tr>
<tr>
<td>Huasco river Chile (UICN, 2012)</td>
<td>Temperate coastal river</td>
<td>3</td>
<td>6.2</td>
<td>80.6</td>
<td>1.07</td>
<td>54 (53-45)</td>
</tr>
<tr>
<td>Voijm dam, Sweden (Renofalt, Jansson et al. 2010)</td>
<td>Polar freshwater</td>
<td>3</td>
<td>39.0</td>
<td>51.3</td>
<td>0.20</td>
<td>43 (71-32)</td>
</tr>
<tr>
<td>Alaska (Estes 1998)</td>
<td>Polar freshwater</td>
<td>3</td>
<td>284.0</td>
<td>21.5</td>
<td>0.21</td>
<td>30 (59-25)</td>
</tr>
<tr>
<td>Hong Kong, China (Niu and Dudgeon 2011)</td>
<td>Tropical floodplain</td>
<td>3</td>
<td>1119.0</td>
<td>12.0</td>
<td>0.11</td>
<td>38 (67-32)</td>
</tr>
<tr>
<td>Vietnam, (Babel, Dinh et al. 2012)</td>
<td>Tropical and subtrop coastal river</td>
<td>1</td>
<td>133.5</td>
<td>15.4</td>
<td>0.16</td>
<td>39 (51-32)</td>
</tr>
<tr>
<td>Tanzania (Kashaigili, McCartney et al. 2007)</td>
<td>Tropical and subtrop coastal river</td>
<td>1</td>
<td>245.0</td>
<td>6.4</td>
<td>0.07</td>
<td>25 (61-19)</td>
</tr>
</tbody>
</table>
Outline

• Problem (1): how to solve EFRs at global scale?
  – What has been done? Smakhtin case
  – Bridging a gap between ecological local case studies and global EF methods
  – Use of 5 hydrological EF methods compared with local case studies
  – Implementation in LPJml (with the aim to define better water availability taking into account EFRs)

• Conclusion
Environmental flow methods: comparison at local and global scale

<table>
<thead>
<tr>
<th>Hydrological season</th>
<th>Flow quantile methods</th>
<th>% MAF</th>
<th>% MMF methods</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Smakthin (2004)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Q90 _Q50 (Pastor, 2013)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tennant (1976)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low flow</td>
<td>Q90</td>
<td>20% MAF</td>
<td>100% MMF</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>60% MMF</td>
</tr>
<tr>
<td>High flow</td>
<td>0 to 20% MAF</td>
<td>40% MAF</td>
<td>40% MMF</td>
</tr>
<tr>
<td></td>
<td>Q50</td>
<td></td>
<td>30% MMF</td>
</tr>
<tr>
<td>Intermediate flow</td>
<td></td>
<td></td>
<td>40% MAF</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>45% MMF</td>
</tr>
</tbody>
</table>

- MAF: mean annual flow
- MMF: mean monthly flow
High flow requirements = \( Q_{50} \)

Low flow requirements = \( Q_{90} \)
High flow requirements = 40% MAF

Low flow requirements = 20% MAF

Tennant (1976)
High flow requirements = 40% MMF

Intermediate flow requirements = 40% MAF

Low flow requirements = 100% MMF
Variable Monthly Flow method (Pastor, 2013)

High flow requirements = 30% MMF

Intermediate flow requirements = 45% MMF

Low flow requirements = 60% MMF
Comparison study
Xeric freshwater ecosystem: Iran (Intermittent river)

GEFC and IHA defined EFR = 30-40% of MAF (Yasi et al. 2012)

- MAF: 5.3 m3.s-1
- Q90: 0.1 m3.s-1
- Q90/MAF = 21
- CV = 0.22

- EFR (Smakhtin) = 19%
- EFR (VMF) = 35%

GEFC and IHA defined EFR = 30-40% of MAF (Yasi et al. 2012)
Tropical and variable freshwater ecosystem: Hong Kong stream

- **Mean monthly flow (m3.s⁻¹)**
  - **MAF**: 1119 m3.s⁻¹
  - **Q90**: 134 m3.s⁻¹
  - **Q90/MAF**: 12 %
  - **CV**: 0.11

- **EFR (study)**: 53 %
- **EFR (Smakhtin)**: 28 %
- **EFR (VMF)**: 35 %

EFR based on sampling of macro-invertebrates of the Hong Kong streams (Niu et al. 2011)
Temperate freshwater ecosystem: Chile (perennial river)

Mean monthly flow (m3.s-1)

Local EF method: Phabsim – habitat simulation model based on salmonids (Pouilly and aguilera, 2012)

- MAF: 6.2 m3.s-1
- Q90: 5 m3.s-1
- Q90/MAF = 80%
- CV = 1.07
- EFR (study) = 34 %
- EFR (Smakhtin) = 81 %
- EFR (VFM) = 30 %
Conclusion from study cases

- Environmental flow requirements (EFRs) average = 37% Mean annual flow (25-54% MAF)
- Low Flow Requirements (LFRs) = 56% Low Flows
- High flow requirements (HFRs) = 34% High Flows
Pro’s – Con’s of those methods

• Quantile methods such as Smakhtin, Q90_Q50 underestimates EFRs of variable rivers and overestimates EFRs of perennial rivers
• Tennant method is only suitable for temperate cases
• Variable Monthly Flow method and Tessmann (%MMF) methods showed good estimates of EFRs although can underestimate high flow requirements
• The use of those 5 five methods can give a range of EFRs at global and river basin scale
Outline

• Problem (1): how to solve EFRs at global scale?
  – What has been done? Smakhtin case
  – Bridging a gap between ecological local case studies and global EF methods
  – Use of 5 hydrological EF validated with local case studies
    – Implementation of EFRs into a global hydrological model LPJml

• Conclusion
LPJmL – a global vegetation and hydrological model

9 natural plant types

3 bioenergy plant types

12 rainfed / irrigated crop types

grazing land
Ratio of EFR/monthly flow in April

Variable Monthly flow (Pastor, 2013)

Tennant, 1976

Tessmann, 1980

Smakhtin, 2004

Q90_Q50 (Pastor, 2013)
ENVIRONMENTAL FLOW DEFICIT = AVAILABLE DISCHARGE – IRRIGATION-EFR
Conclusion

• Until now, EFRs were poorly assessed at global scale
• Here, we present a “validation” of VMF method with local case studies
• Inclusion of intra-annual variability (monthly step)
• Inclusion of longitudinal connectivity (grid cell calculation – aggregated to river basin)
• Range of EF method to tackle uncertainty
• We can already spatially recognized areas where EFRs are not satisfied (South Asia, West US, middle east)
• There is a need for harmonization/evaluation of the ecological status of river basin worldwide
QUESTIONS ??
QUESTIONS ??

Table 2.1 Smakhtin conceptual EFR method (Smakhtin et al., 2004a).

<table>
<thead>
<tr>
<th>Low Flow Requirement ($Q_{90}$; LFR)</th>
<th>High Flow Requirement (HFR)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>If $Q_{90} &lt; 10%$ mean discharge (MAR)</td>
<td>then HFR = 20% MAR</td>
<td>Basin with very variable flow regimes. Most of the flow occurs as flood events during the short wet season.</td>
</tr>
<tr>
<td>If $10%$ MAR $\leq Q_{90} &lt; 20%$ MAR</td>
<td>then HFR = 15% MAR</td>
<td></td>
</tr>
<tr>
<td>If $20%$ MAR $\leq Q_{90} &lt; 30%$ MAR</td>
<td>then HFR = 7% MAR</td>
<td></td>
</tr>
<tr>
<td>If $Q_{90} \geq 30%$MAR</td>
<td>then HFR = 0% MAR</td>
<td>Very stable flow regimes (e.g. groundwater dominated rivers). Flow is consistent throughout the year. Low flow requirement is the primary component.</td>
</tr>
</tbody>
</table>

Low flows = $Q_{90}$  
High flows = $\%$ MAF
Xeric freshwater ecosystem: Iran (Dry variable river)

EFR = 35% of MAF

- EFR (Smakhtin) = 19%
- EFR (VMF) = 35%
Amazon
Comparison EFR in January and July: Amazon river basin

Amazon_January

Amazon_July

EFR in January and July:

- Amazon river basin

Graph: Amazon annual EFR
EFR=22-58% MMF (average 40 years)
Nile
Comparison EFR in January and July: Nile river basin

Nile_January

Nile_July

Nile hydrograph
EFR=30-60% MMF (41 years)
Tropical and variable freshwater ecosystem: Hong Kong stream

Mean monthly flow (m³.s⁻¹)

- EFR (study) = 53 %
- EFR (Smakhtin) = 28 %
- EFR (VMF) = 35 %
Temperate freshwater ecosystem: Chile (Stable river)

Mean monthly flow ($\text{m}^3\text{s}^{-1}$)

- EFR (study) = 34%
- EFR (Smakhtin) = 81%
- EFR (VFM) = 30%
Actual tasks

• Modification of the LPJml code by including EFRs as a 1\textsuperscript{st} water user
• Including EFRs in the reservoir scheme, how much water should be released to the river
Loss of freshwater species higher in tropics!

<table>
<thead>
<tr>
<th>Basin</th>
<th>Fish species</th>
<th>Discharge (m³.s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nile</td>
<td>135</td>
<td>2800</td>
</tr>
<tr>
<td>Amazon</td>
<td>1802</td>
<td>209000</td>
</tr>
<tr>
<td>Mississippi</td>
<td>267</td>
<td>17000</td>
</tr>
<tr>
<td>Indus</td>
<td>151</td>
<td>6600</td>
</tr>
</tbody>
</table>
Previous environmental flow method:
New environmental flow method: Variable Monthly Flow (VMF)

High flow requirements = 30% monthly flow

Intermediate flow requirements = 45% monthly flow

Low flow requirements = 60% monthly flow

Global hydrological and vegetation model: LPJml

• Spatial scale: grid cell or river basin
• Temporal scale: past and future impact of LU and CC
• Can determine:
  – hydrological flow regimes,
  – water availability and variability,
  – degree of modification of river flows (Including dams and reservoirs),
  – water withdrawals and return flows
  – other water uses (households and industries)
Loss of freshwater species higher in tropics!

<table>
<thead>
<tr>
<th>Basin</th>
<th>Fish species</th>
<th>Discharge (m$^3$.s$^{-1}$)</th>
<th>With 50% discharge reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nile</td>
<td>135</td>
<td>2800</td>
<td>32</td>
</tr>
<tr>
<td>Amazon</td>
<td>1802</td>
<td>209000</td>
<td>436</td>
</tr>
<tr>
<td>Mississippi</td>
<td>267</td>
<td>17000</td>
<td>64</td>
</tr>
<tr>
<td>Indus</td>
<td>151</td>
<td>6600</td>
<td>36</td>
</tr>
</tbody>
</table>

Fig. 1  Fish species–discharge curve used to build scenarios of fish loss. The regression was modeled with rivers found between 42°N and 42°S, where reduced discharge is predicted to occur.

Log fish richness = 0.4 × log mean annual discharge (m$^3$.s$^{-1}$) + 0.6242, $r^2 = 0.57$. 
How to continue?

- Our LPJml work can be turned into a rapid water security assessment as far as the bio-physical side is concerned.
- IWMI / WLE cooperation?

(IWMI-led Water Land Ecosystems initiative)
LPJmL – a global vegetation and hydrological model

9 natural plant types

3 bioenergy plant types

12 rainfed / irrigated crop types

grazing land
High flow period | Low flow period

Mean annual flow
Where EFRs are not satisfied?

Net discharge = actual discharge – EFRs
Using a range of EF methods in different river basins

EFR amazon = 30-65% of MAF
EFR amazon = 12-48% of MAF