Impact assessment of water consumption in LCA

2012

Introduction

Introduction

- Water use in LCA has been widely neglected in the past
  - Mainly in agriculture (more recent focus in LCA)
  - Water consumption less relevant in northern European countries
  - Water is a cheap resource (often not recorded)
  - Leading LCI databases such as ecoinvent have unsufficient information on water use

Regionalization is required

- On global average, there is no water scarcity
- Different impacts – different regions/archetypes:
  - Ecosystems
  - Humans
  - Stock/fund resources
- Inventory
  - Water consumption mainly relevant in agriculture – regional aspect crucial (also on inventory level)

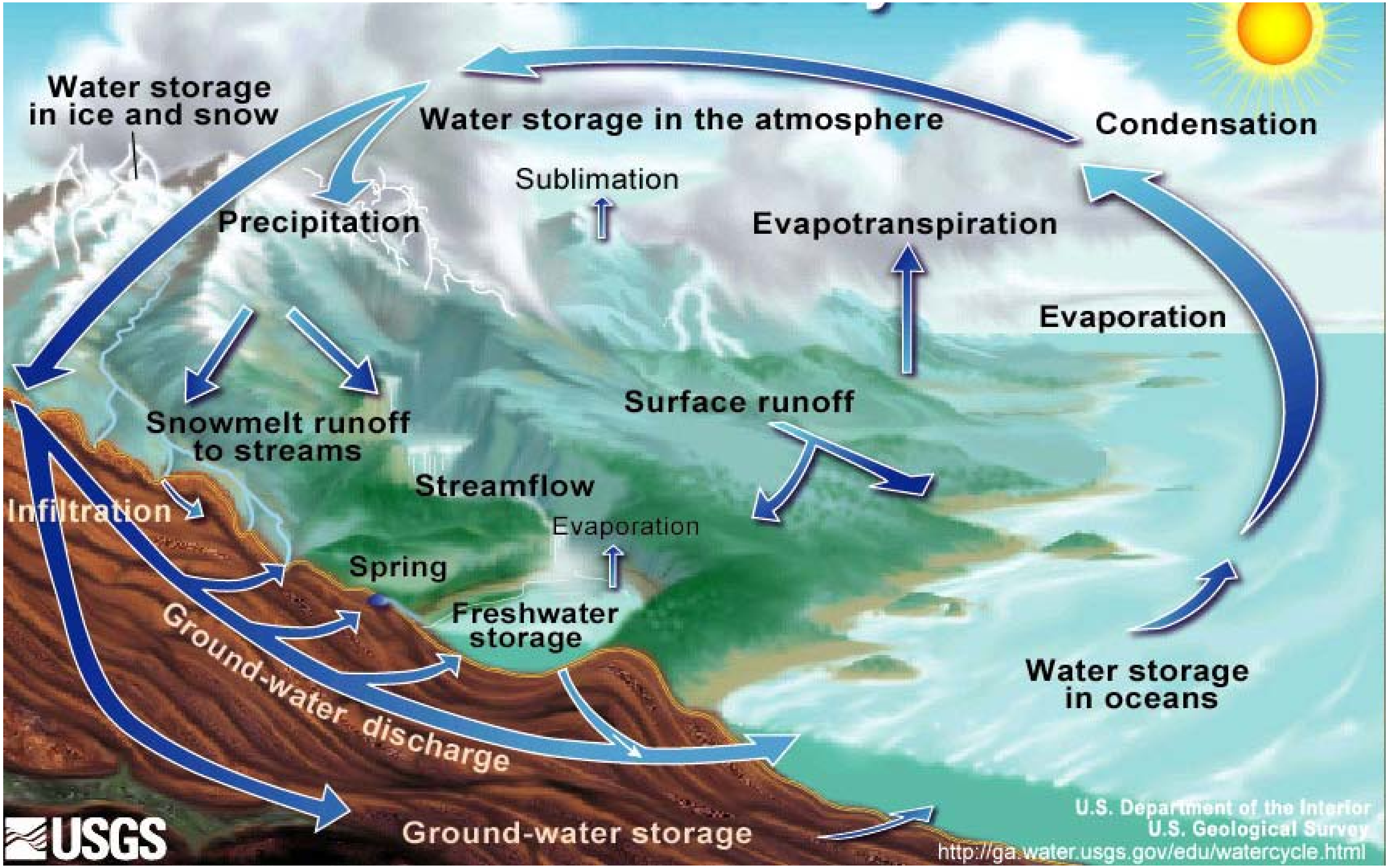
Challenges

- Increased complexity (time requirements for LCA)
- Regionalized inventory data
- Regional supply chains
  - Connected with socio-economic circumstances
- Uncertainties (inventory & impacts)
  - New problem: picking the wrong location
- Software implementation & applicability
  - So far no LCA software can handle regionalized LCA

Water resources overview

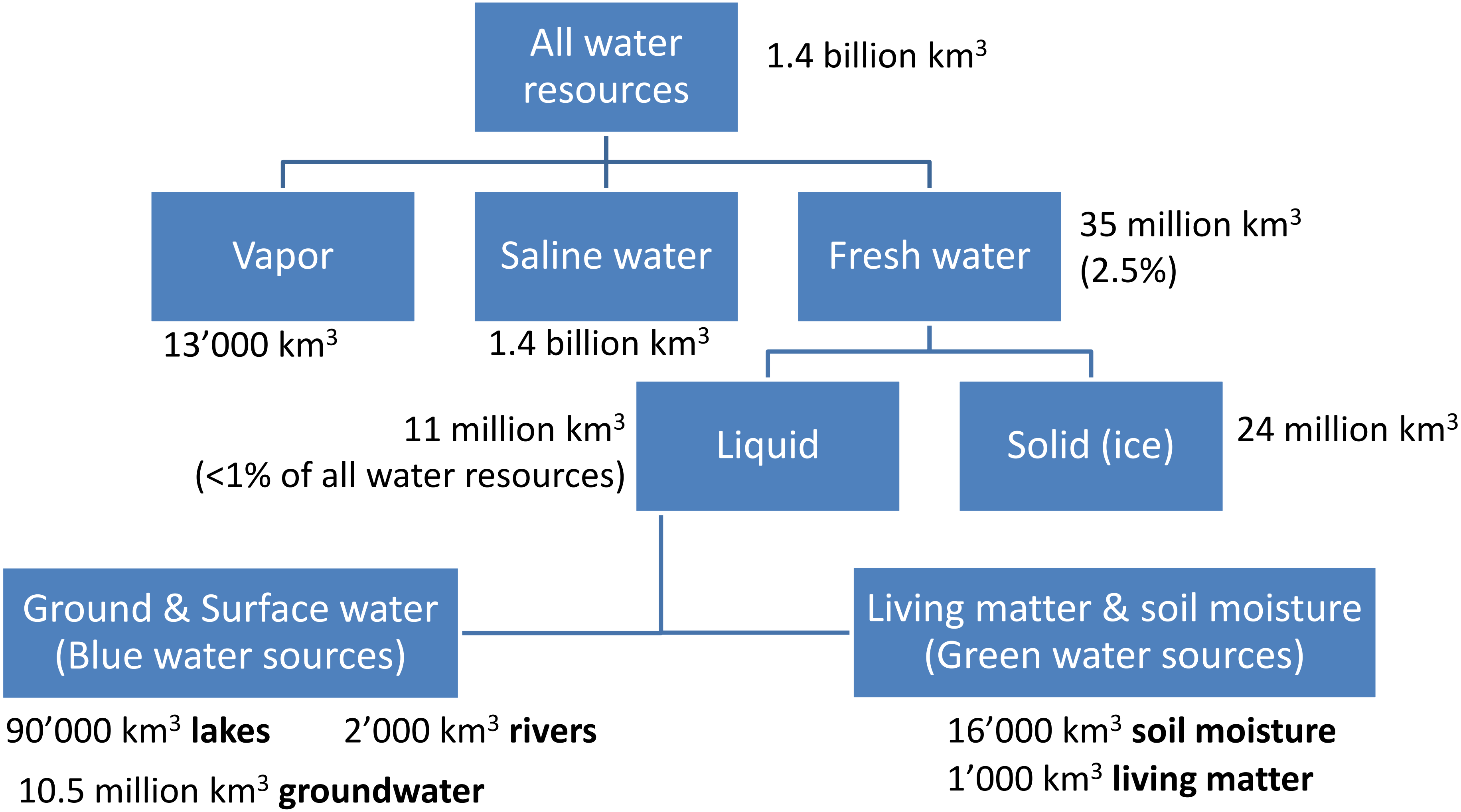
Natural cycle and man-made issues

The Water Cycle



Source: U.S. Department of the Interior | U.S. Geological Survey URL: http://ga.water.usgs.gov/edu/watercycle.html

Hydrosphere - volumes



Source: Shiklomanov and Rodda (2003) ISBN: 0 521 820855

Global average renewal rates

Table 1.14. *Periods of renewal of water resources on the Earth*

Water of hydrosphere	Period of renewal
World Ocean	2 500 years
Ground water	1 400 years
Polar ice	9 700 years
Mountain glaciers	1 600 years
Ground ice of the permafrost zone	10 000 years
Lakes	17 years
Bogs	5 years
Soil moisture	1 year
Channel networks	16 days
Atmospheric moisture	8 days
Biological water	several hours

Flow resource (renewable)

Global annual water flows

- **Precipitation** on land: **100’000** km^3 / year
- **Unproductive evaporation** on land: 23’000 km^3 / year
- Available water (**runoff & transpiration**): **77’000** km^3 / year (Alcamo et al 2003)
  - **Transpiration** (plants): **40’000** km^3 / year (Rost et al. 2008)
    - In crops 6’000 km^3 / year
  - **Runoff**: **35’000** km^3 / year (Rost et al. 2008)
- **Human water use**: **3’600** km^3 / year (Alcamo et al 2003)
- **Irrigation** water consumption: 1’000-**2’000** km^3 / year

Adapted from Aveny GmBH

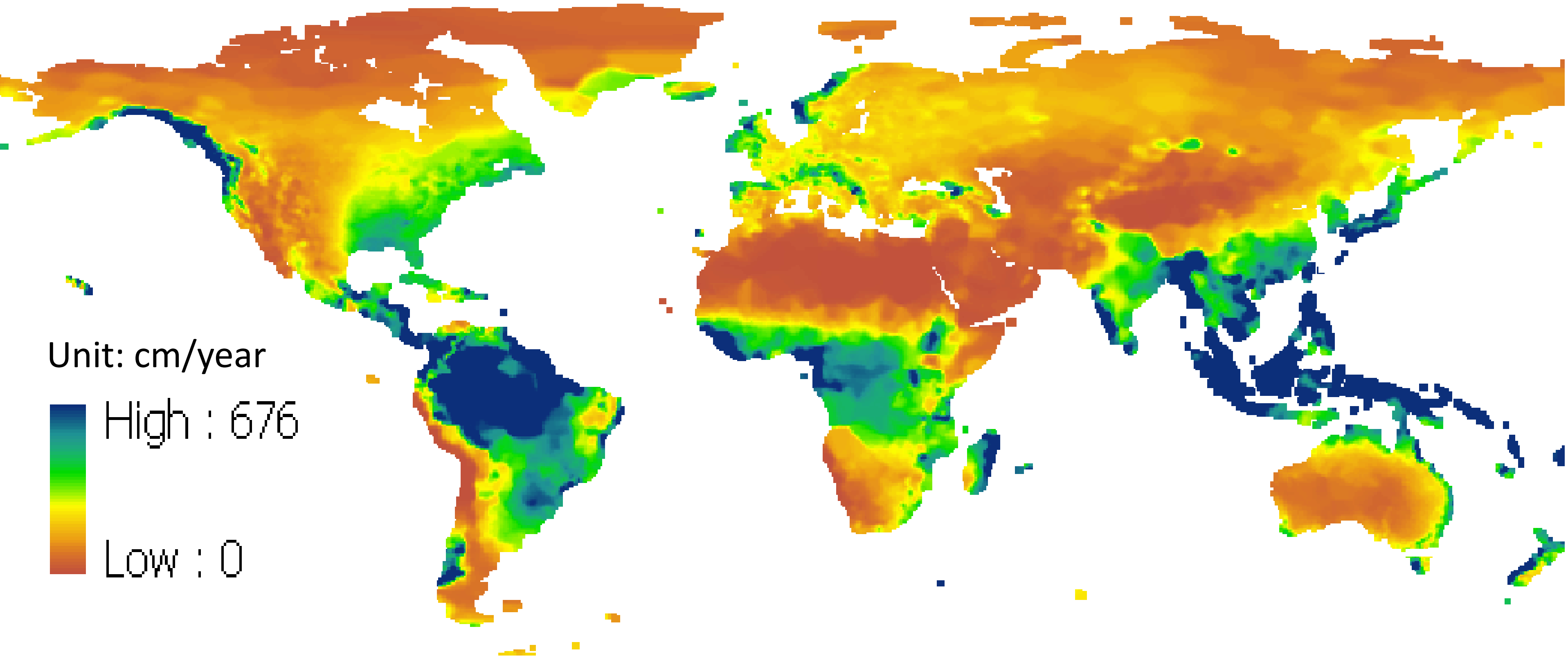
Global water scarcity

- **Runoff**: **35'000** km^3 / year (Rost et al. 2008)
- Suggested **safe operational limit**: 4000 km^3 / year (Rockström et al. *Nature* ***2009)***

→ ***BUT: Distribution problem!***

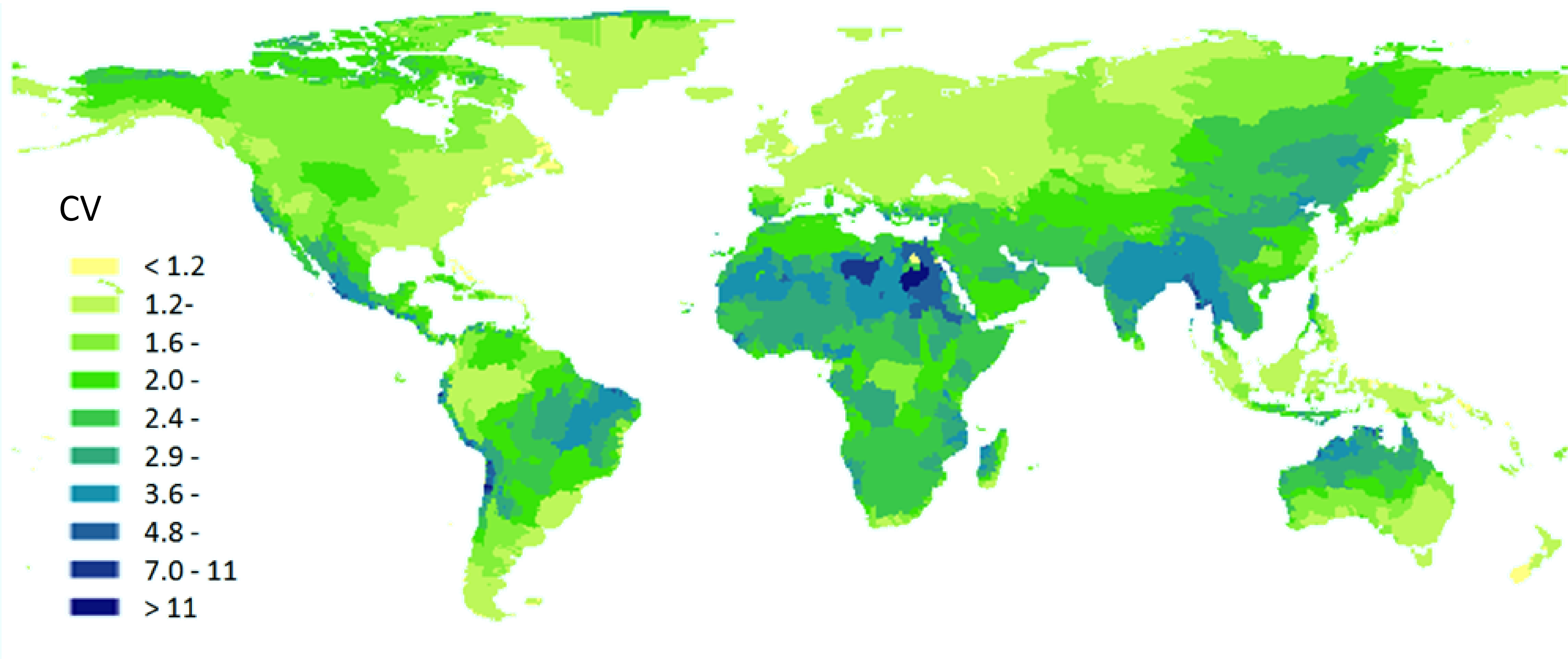
Precipitation distribution

Relevance of location



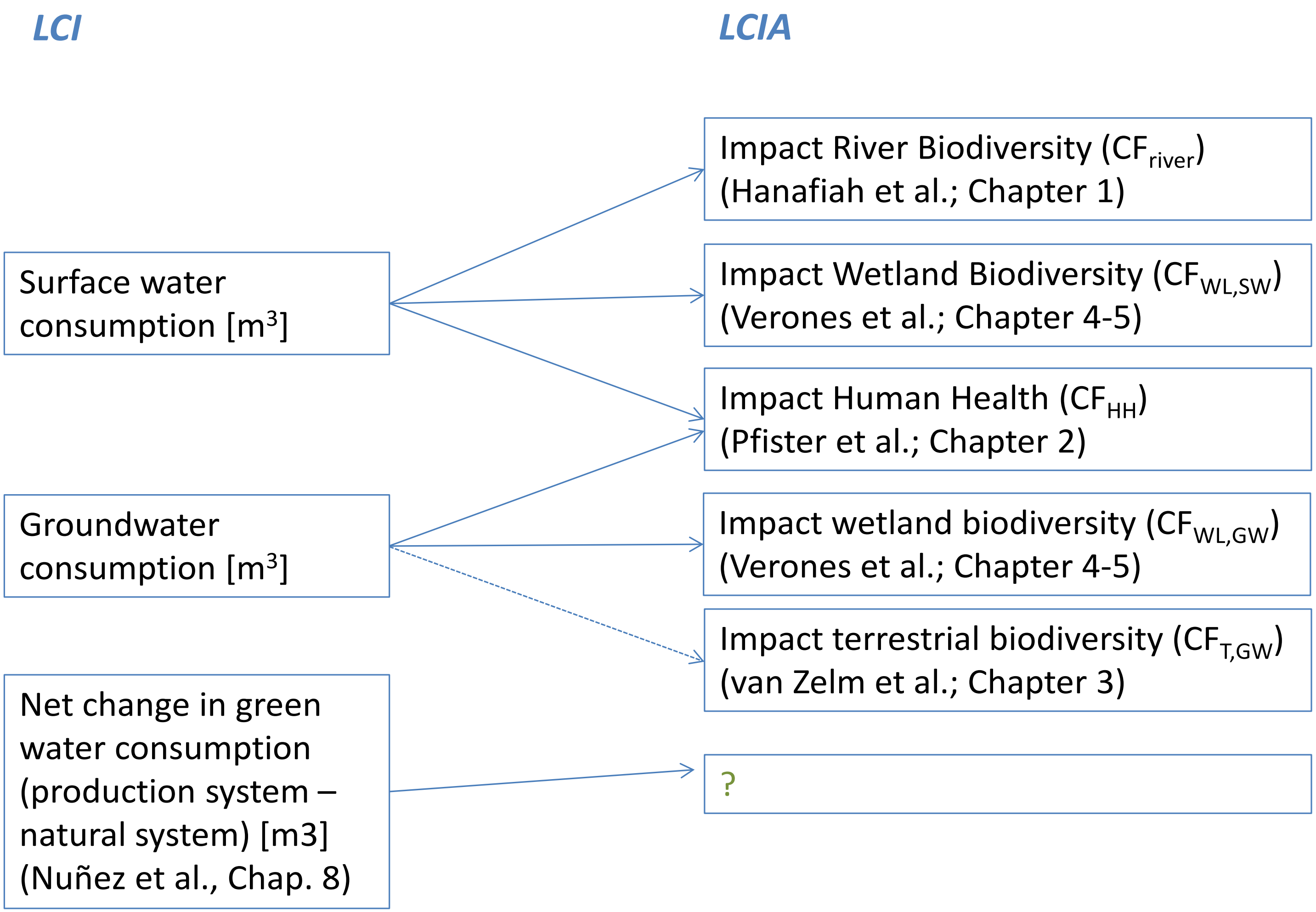
Precipitation variability (temporal distribution)

Coefficient of Variation (STD/mean) of monthly precipitation



Structure of LC-Impact methods for water use

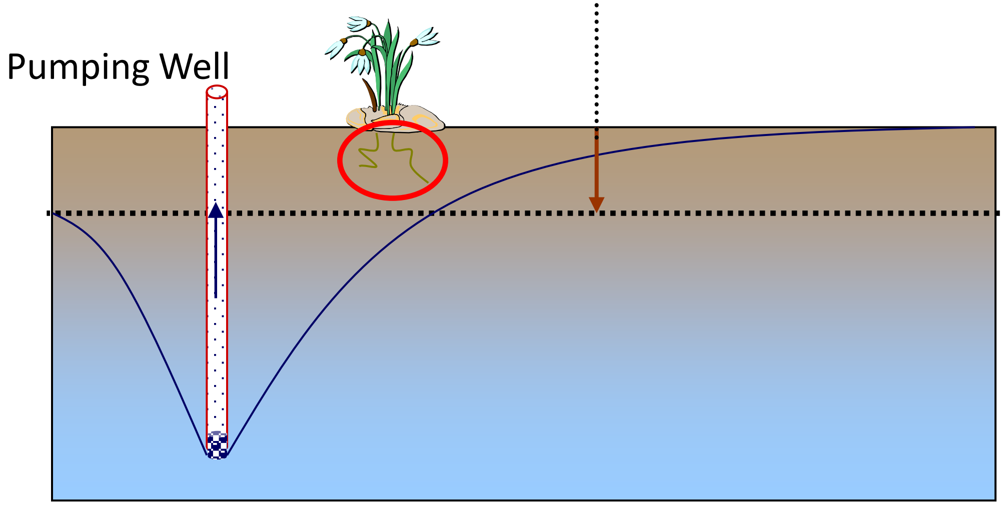
Overview of developed LCIA factors



Impacts on ecosystem quality

- Impacts on terrestrial biodiversity
- Impacts on river biodiversity
- Impacts on specific wetland biodiversity

Van Zelm et al: Groundwater extraction



→ Potentially Not Occurring Fraction of Plant Species (PNOF)

Extraction → Lowering water level → Damage to environment

Fate $A_i * \Delta AG_i / \Delta Q_i$

Groundwater model based on MODFLOW

Effect $dPNOF_i / dAG_i$

Multiple regression curves (MOVE model)

AG = Average Groundwater level (m)

Q = Extraction rate (m^3/yr)

D = Damage (-)

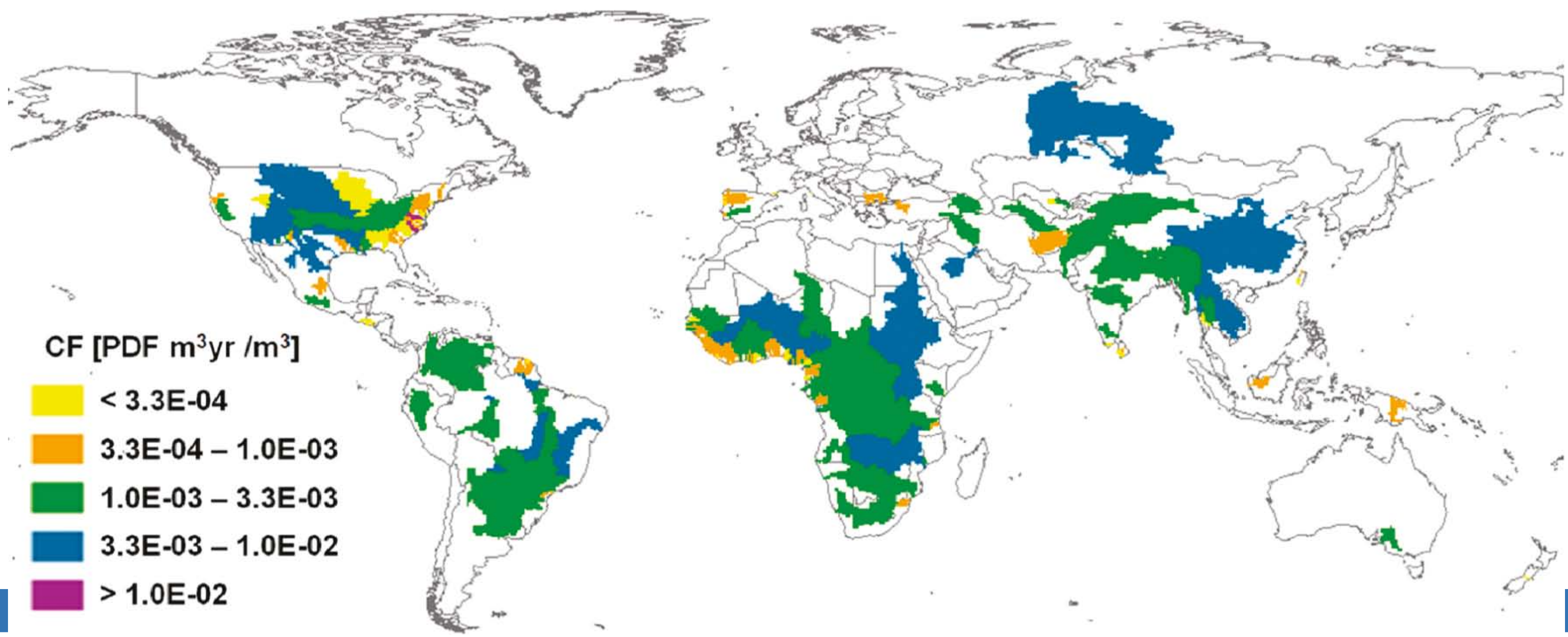
- Data available for the Netherlands
- 625 terrestrial plant species; 141 on red list
- Endpoint level

Hanafiah et al. 2011: Reduced river flow

- Reduced fish species as a function of reduced river flow (Q)

$$CF_{wc,i} = FF_i \cdot EF_i = \underbrace{\frac{dQ_{mouth,i}}{dW_i}}_{fate} \cdot \underbrace{\left(\frac{dPDF_i}{dQ_{mouth,i}} \cdot V_i \right)}_{effect}$$

W = water consumption
PDF = potentially disappeared fraction of species
V = river volume



Impacts of water consumption on wetland biodiversity

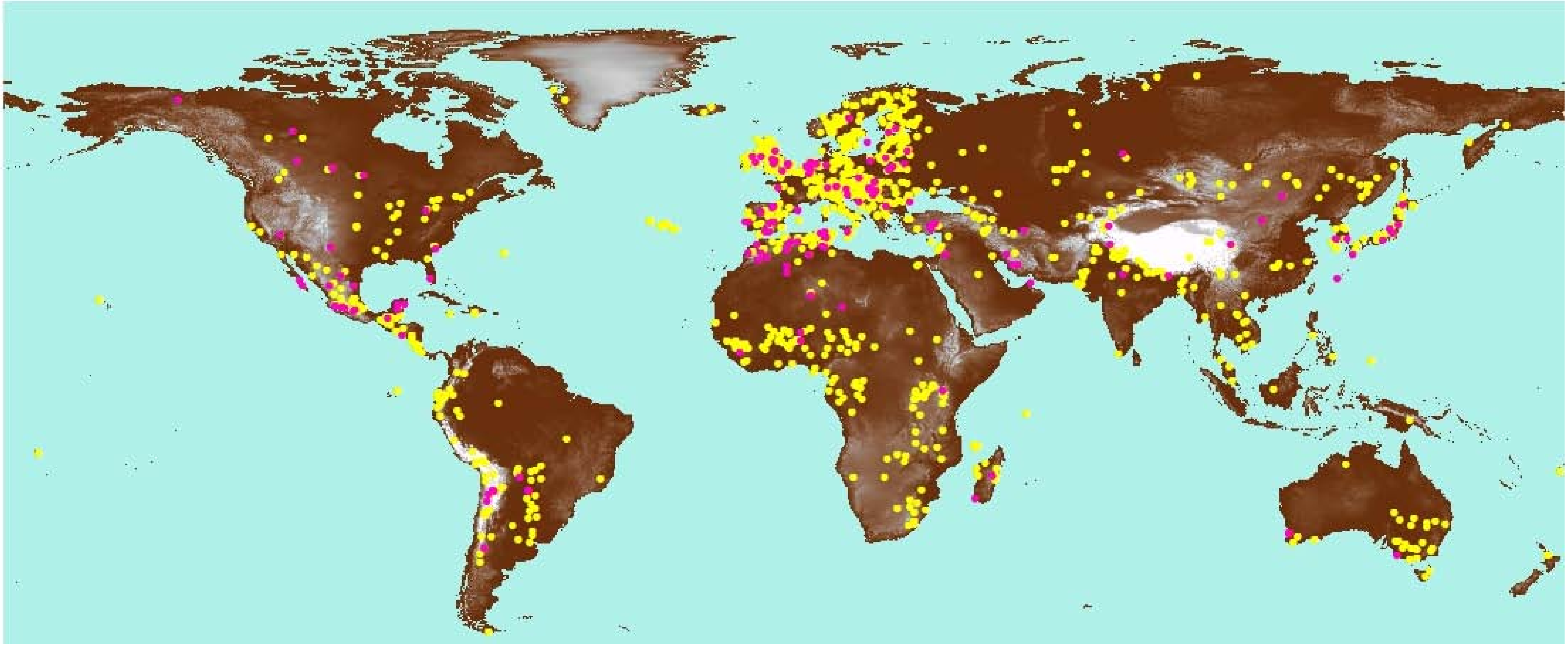
Definition of wetlands

Very diverse types and (often) species-rich

Ramsar Convention: «[…] areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres»

Wetlands of international importance

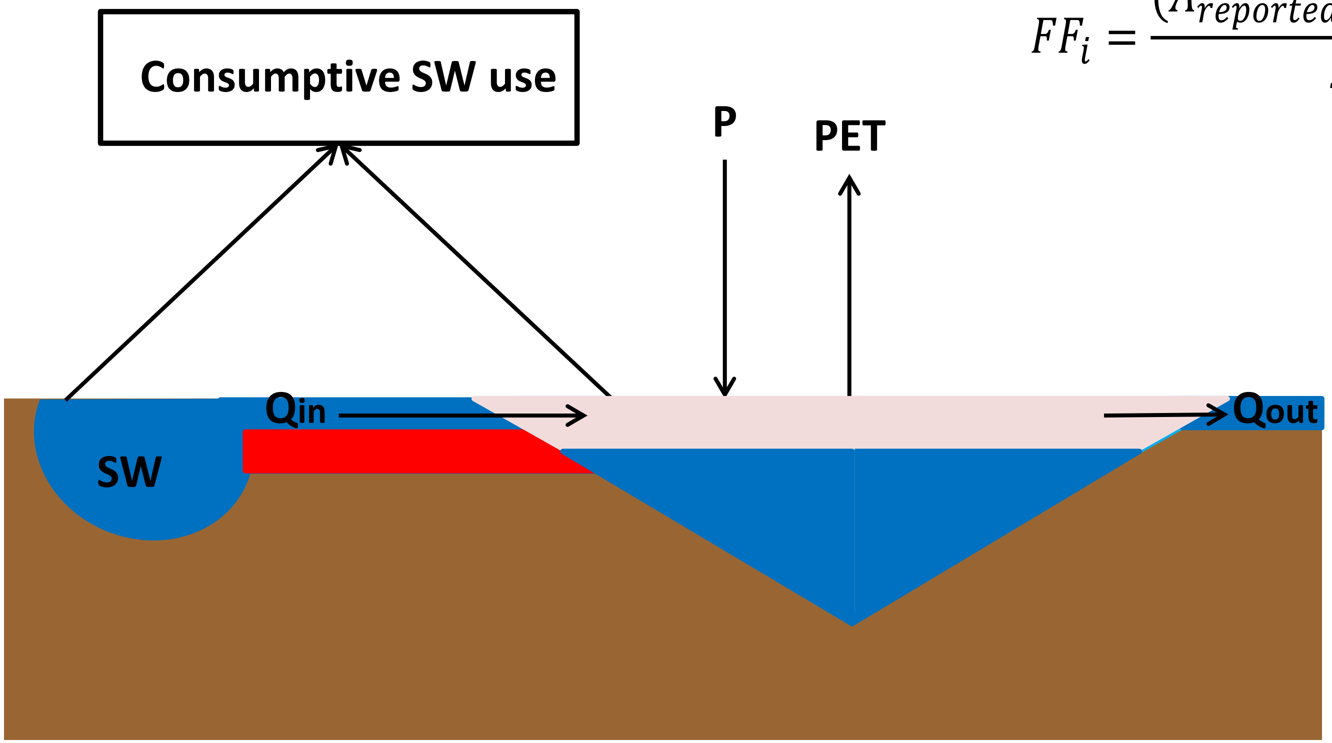
- 1184 inland wetlands of international importance
- 1033 surface water-fed, 151 groundwater-fed



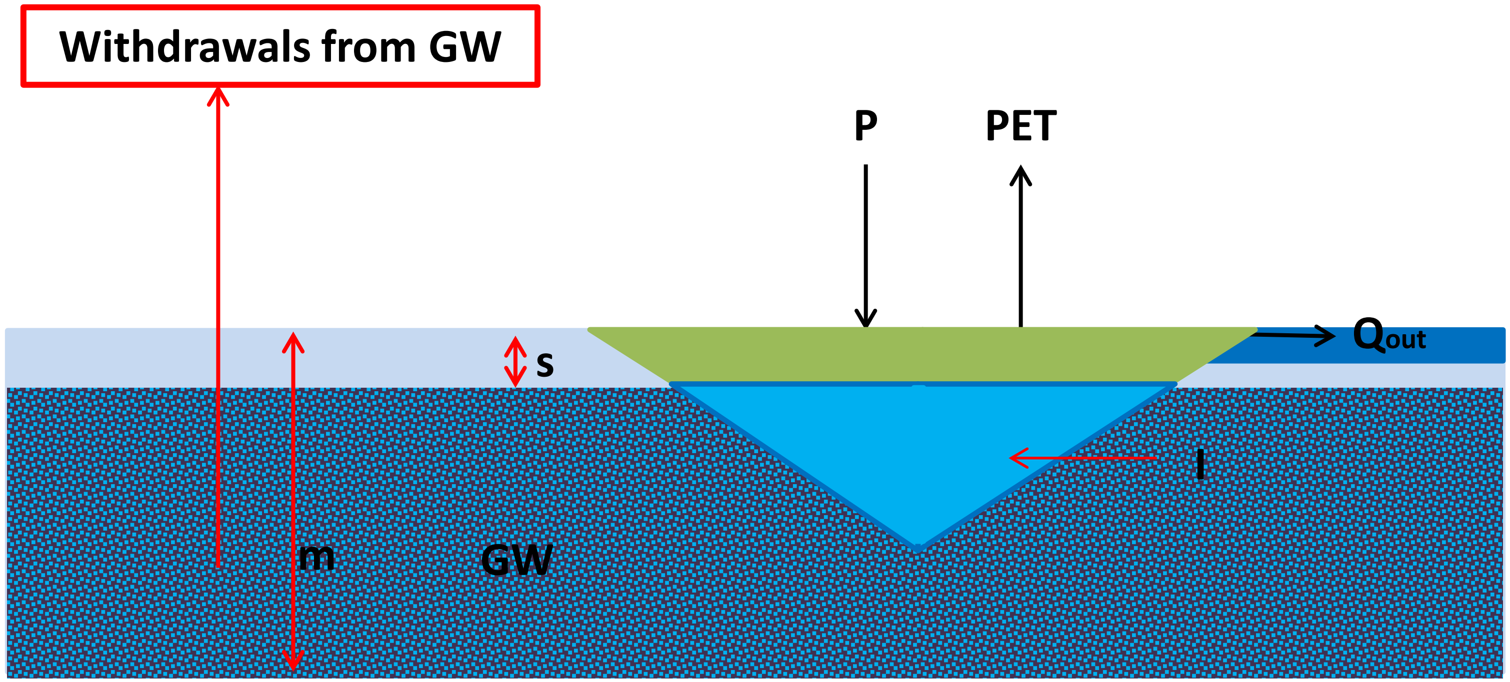
Fate factors: Surface water-fed wetlands

Simplified hydrological balancing for each wetland site

$$FF_i = \frac{(A_{reported,i} - A_{new,i})}{x_i}$$



Fate factors: Groundwater-fed wetlands

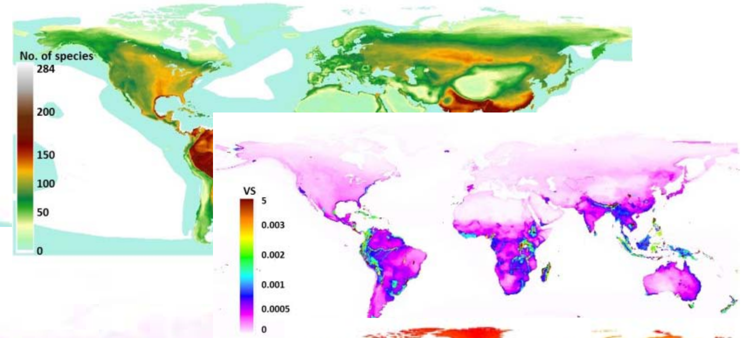


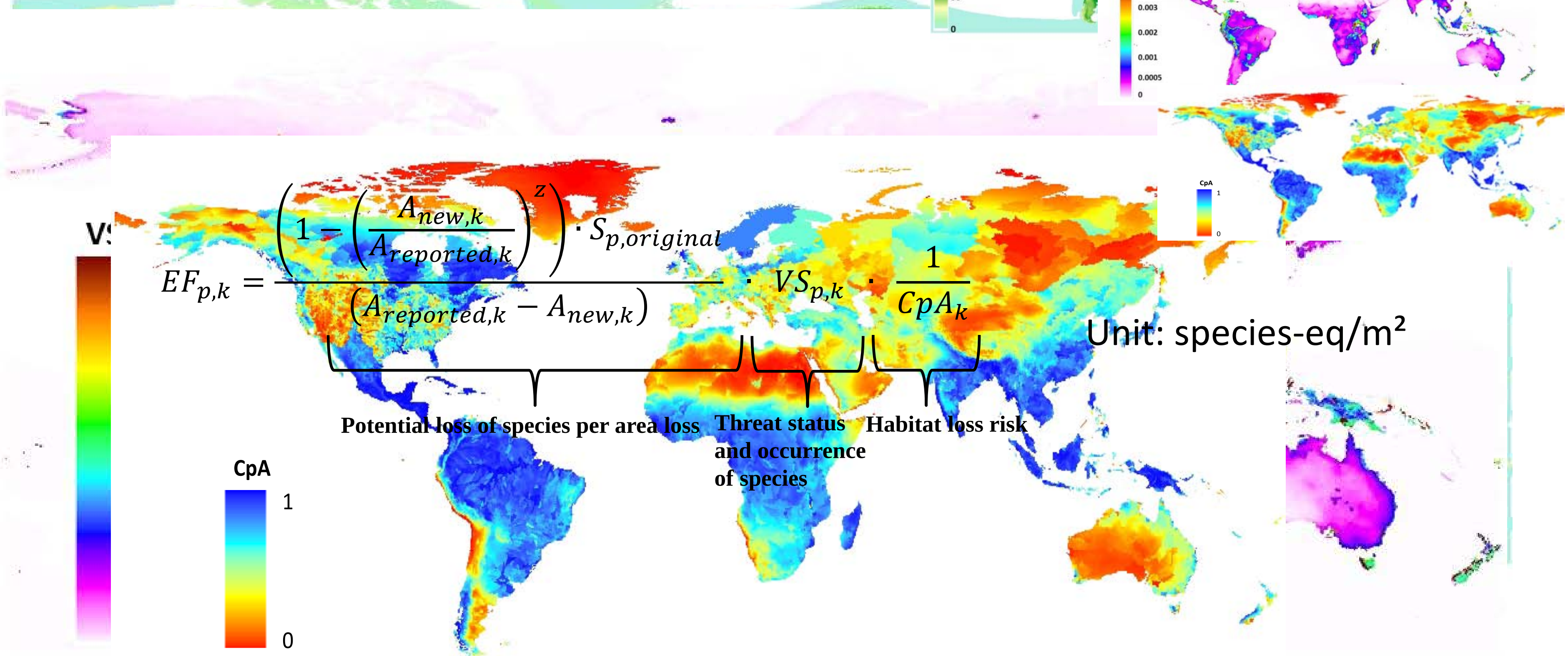
Effect factors (I)

- Factors for
  - Waterbirds
  - Non-residential birds
  - Amphibians
  - Reptiles
  - Water-dependent mammals

Effect factors (II)

1. Species richness maps
2. Vulnerability score
3. CpA: Habitat loss risk



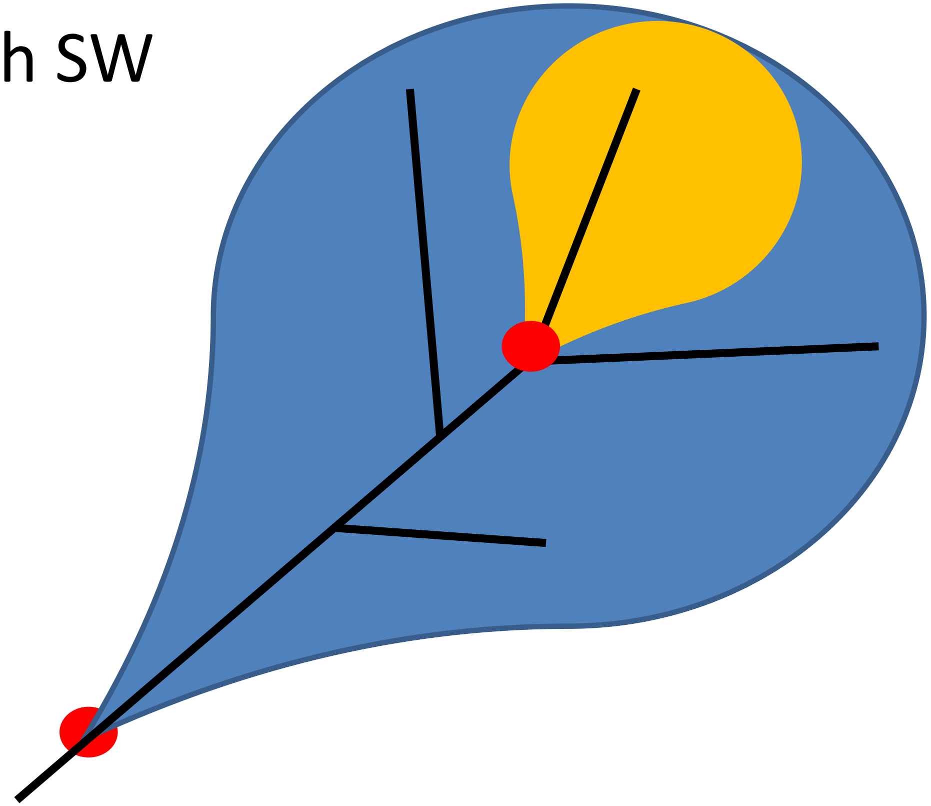


$$EF_{p,k} = \frac{\left(1-\left(\frac{A_{new,k}}{A_{reported,k}}\right)^{z}\right)\cdot S_{p,original}}{\left(A_{reported,k}-A_{new,k}\right)} \cdot VS_{p,k} \cdot \frac{1}{CpA_k}$$

Unit: species-eq/m²

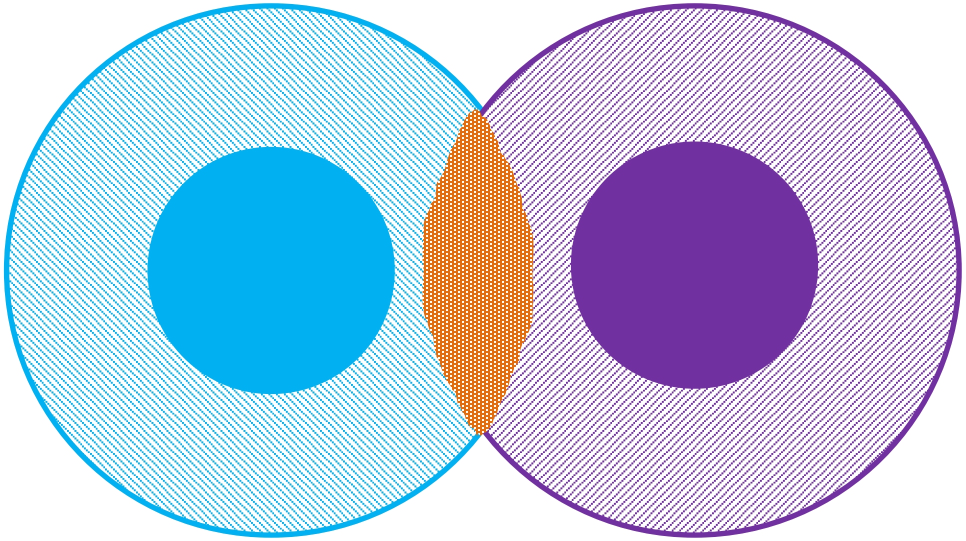
Characterization factors

- Delineation of watershed for each SW wetland



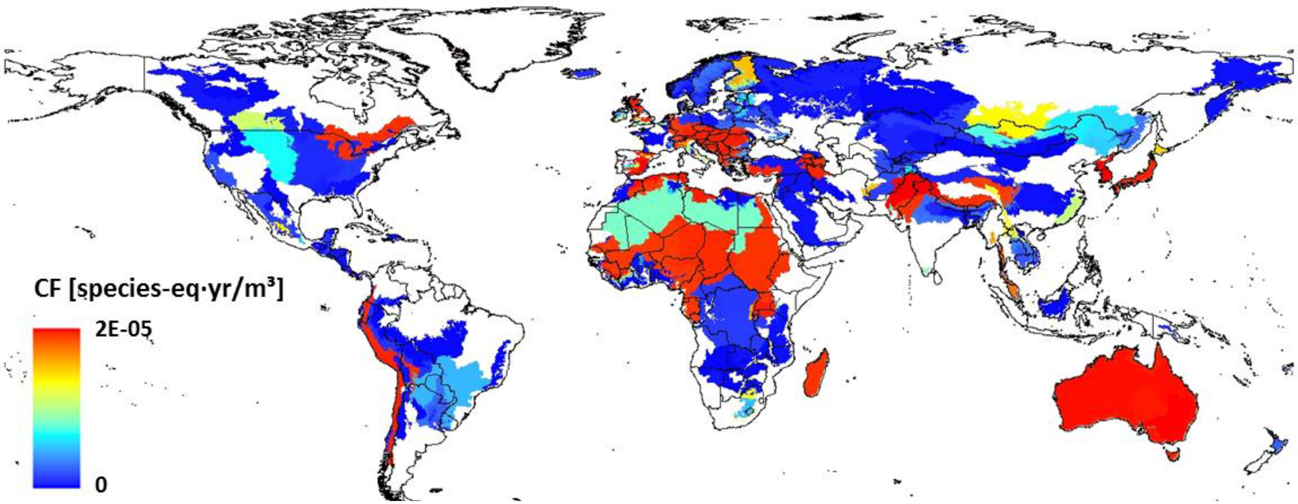
Characterization factors

- Delineation of Areas of Relevance for each GW wetland

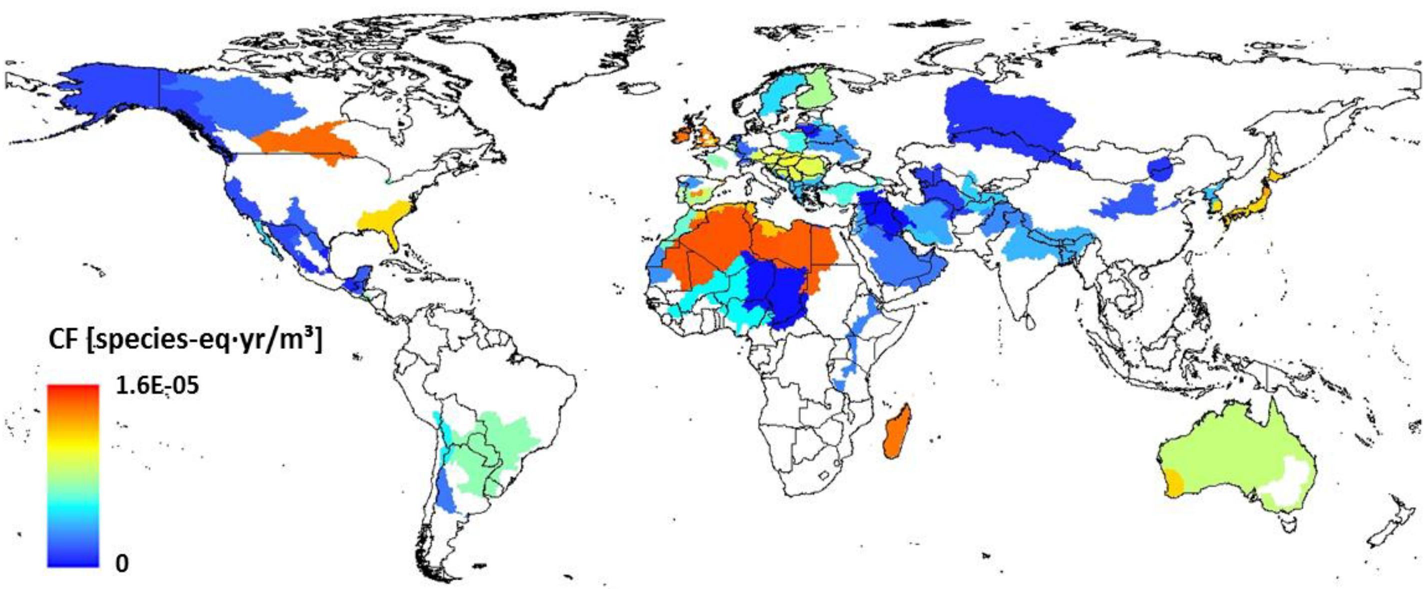


Results (example for waterbirds)

SW

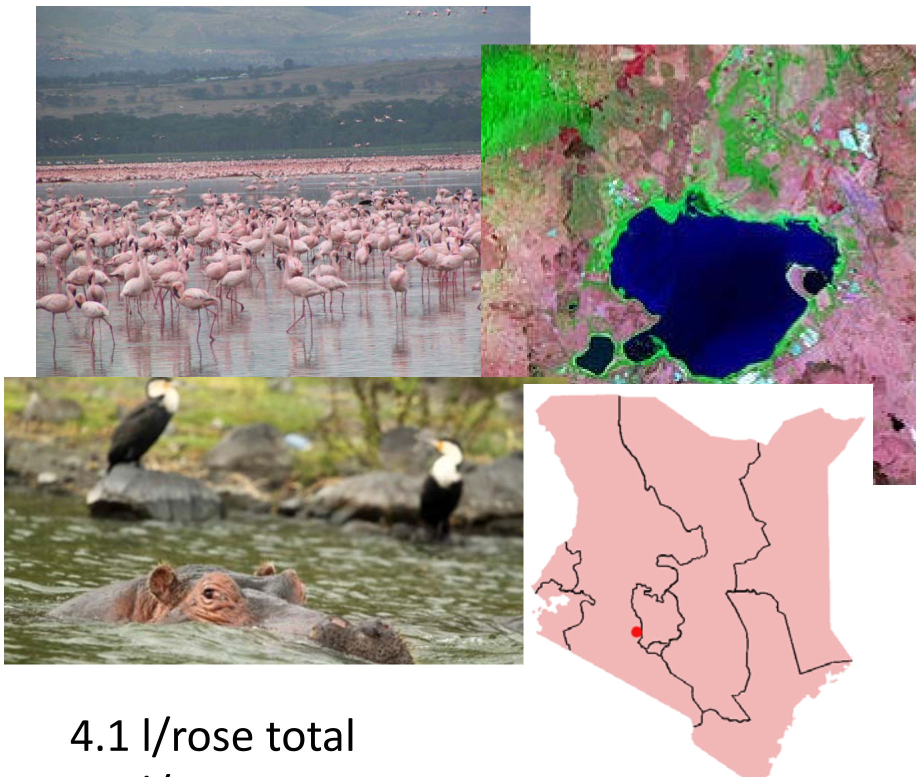


GW



Application example (only water consumption) (I)

- Production of a bunch of 10 roses in Kenya and the Netherlands

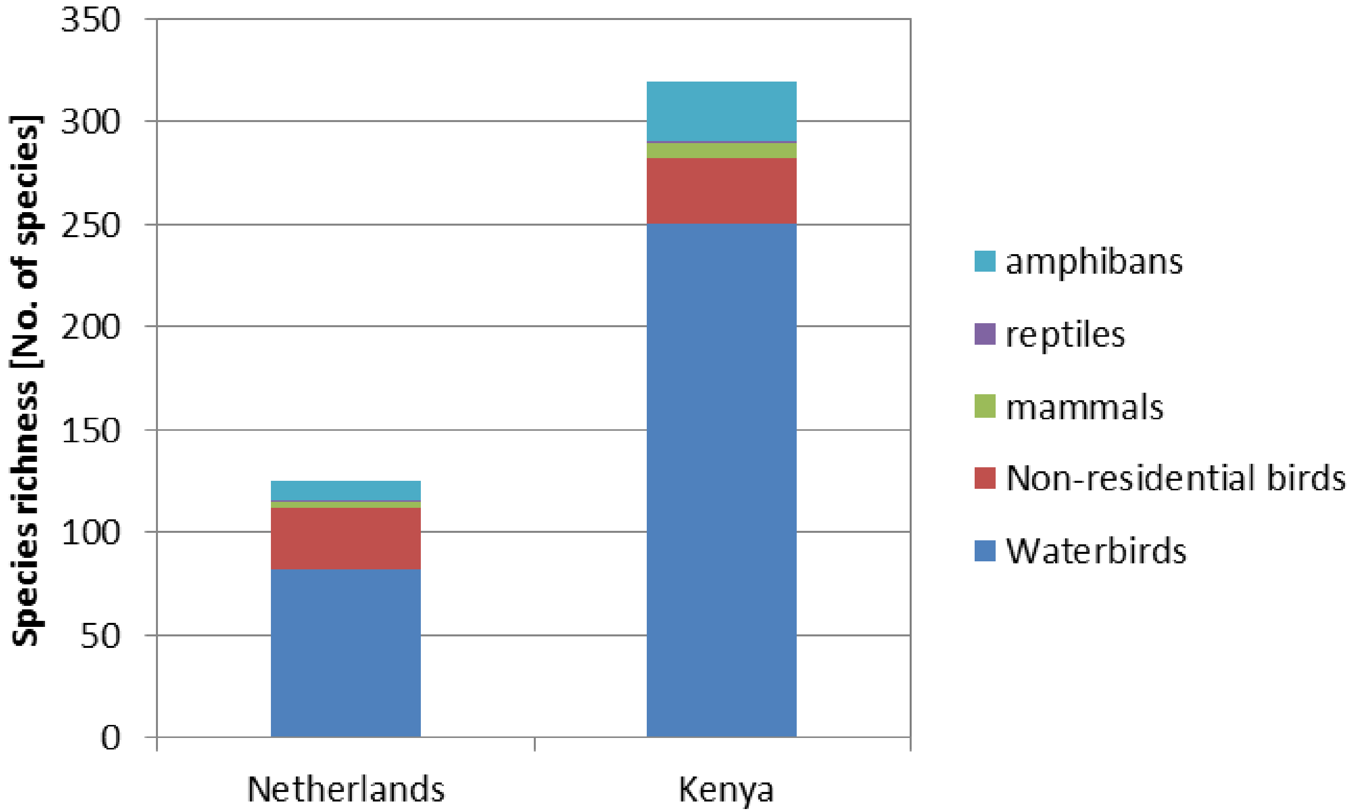


4.1 l/rose total
3.4 l/rose SW
0.7 l/rose GW

3.3 l/rose total
1.6 l/rose SW
0 l/rose GW

Sources: http://www.kenyaweeklypost.com/modules.php?name=News&file=article&sid=1487
http://en.wikipedia.org/wiki/Lake_Naivasha
http://www.nature.org/ourinitiatives/regions/africa/elly-goes-home-new-school-and-naivasha.xml
http://flickrhivemind.net/Tags/vanmiddag/Recent
http://www.flickr.com/photos/dennis87/390085669/
http://en.wikipedia.org/wiki/File:LocatieBleiswijk.png

Application example (only water consumption) (II)



+ Vulnerability, CpA,

+ Amount of water consumed, source of water consumed

Potential future improvements

- Larger coverage of wetlands (not only such of international importance)
- If better hydrogeological data is available (some time)→ reduce uncertainties
- Consider interactions between surface water and groundwater

Local case study

- Differences to global approach
  - Better data availability
  - Site-specific conditions can be taken into account

- More detailed modelling possible
  - Water balances for different scenarios
  - Salinity balances
  - Temporal and spatial explicit modeling of thermal plume

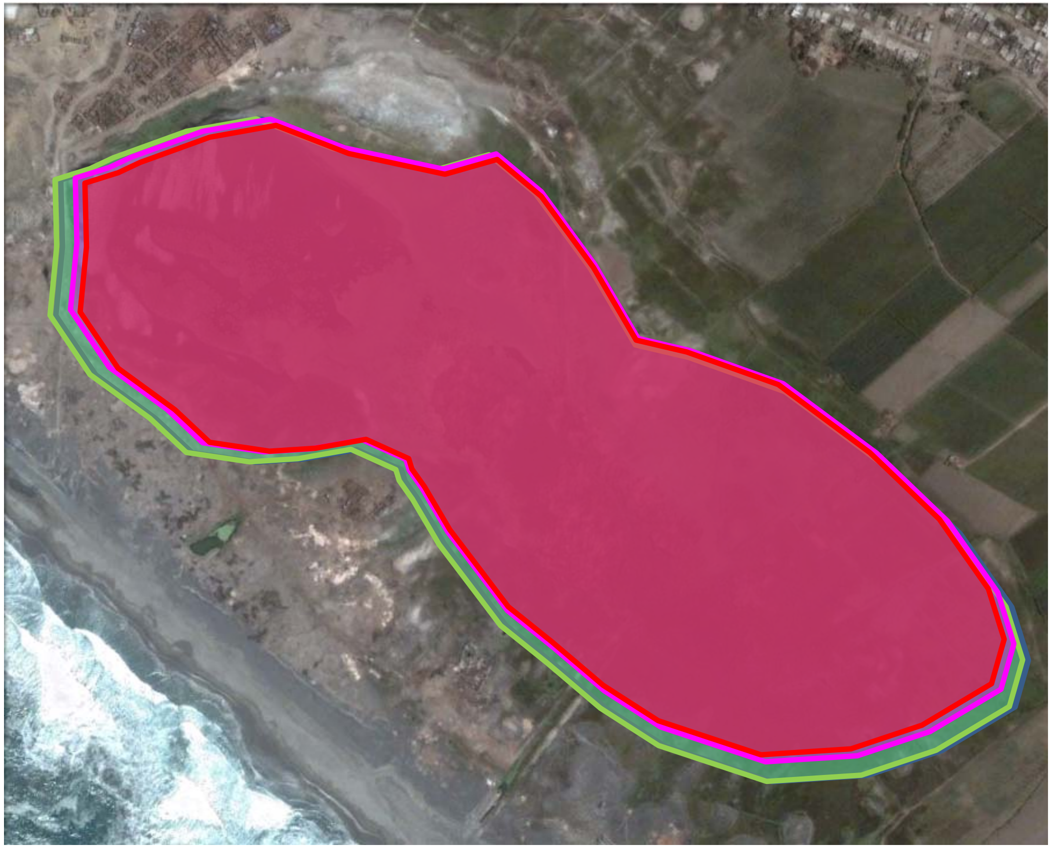
Local case study: Peru

- Chancay-Huaral, Peru
- 3095 km² in total
- 1245 km² in lower valley
- Rio Chancay-Huaral
  - 30 mm/a precipitation
  - 260 km² irrigated agriculture
  - Natural vegetation: 36 ha->Santa Rosa

Source map: http://perumuchopordescubrir.blogspot.com/2011/01/conociendo-la-provincia-de-huaral.html

Local case study: Peru

- Area changes for each scenario (2020):
  - Asparagus:+0.01ha
  - Drip irrigation:-0.4ha
  - No irrigation:-2ha



Impacts of water consumption on the salinity in wetlands

Local case study: Spain

- Albufera de Adra

Map source: Google earth

Fate factor

- Water balances
  - Dry months
  - Wet months
- Salt balances
  - Dry months
  - Wet months
- Solving with GAMS

$$FF = \frac{\Delta FGW}{\Delta \mathrm{ETcrop}} \frac{\Delta C_N . V_N}{\Delta FGW} [\mathrm{g} \cdot \mathrm{l}^{-1} \cdot \mathrm{m}^3 \cdot \mathrm{yr} \cdot \mathrm{m}^{-3}]$$

Effect factor

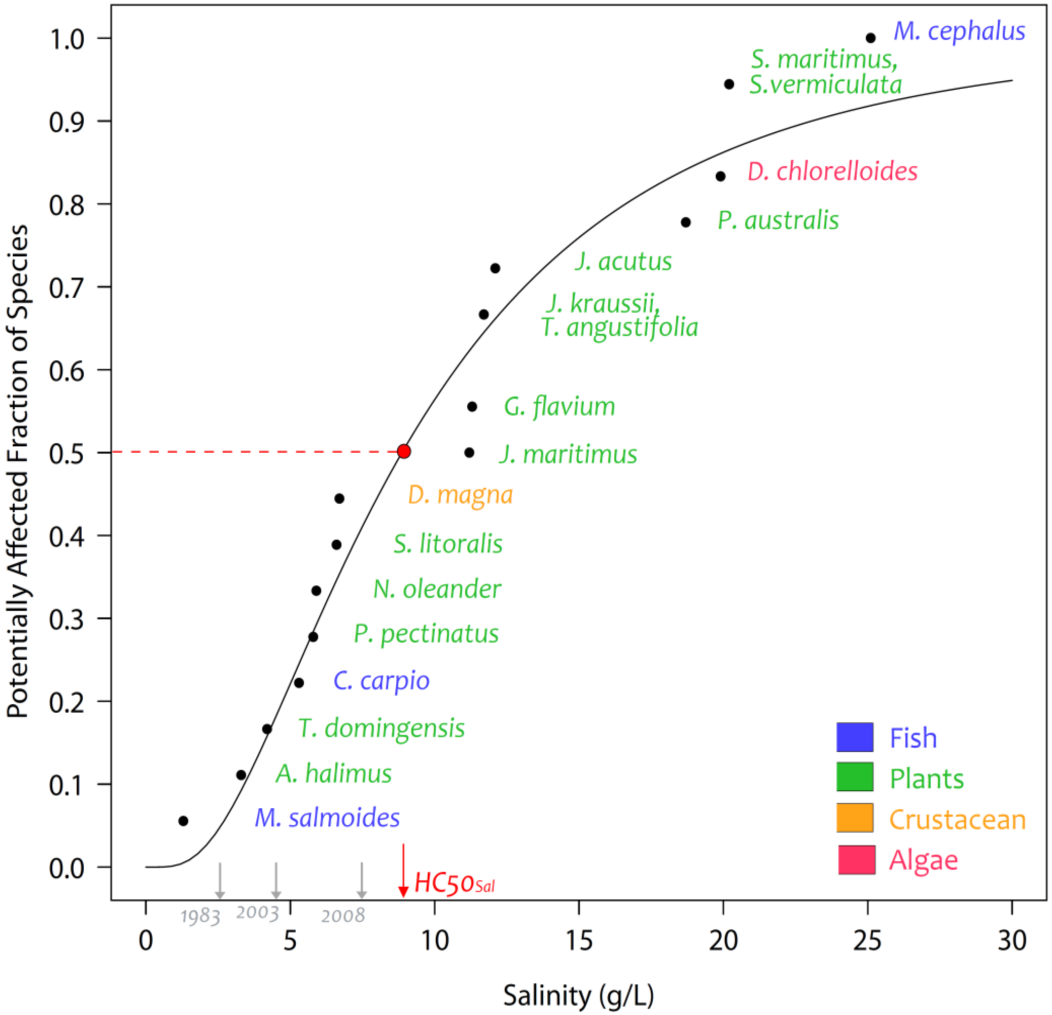
- Based on SSD for salinity
- EC50s for different local species

$$EF_{Sal} = \frac{\Delta PAF_{Sal}}{\Delta Sal} = \frac{0.5}{HC50_{Sal}} \quad [\mathrm{PAF} \cdot \mathrm{l} \cdot \mathrm{g}^{-1}]$$

Results - Fate factor

- Sensitive to changes in salinity
- Varies between:
  - Max 6.72 $g \cdot l^{-1} \cdot m^3 \cdot yr \cdot m^{-3}$
  - Min 0.25 $g \cdot l^{-1} \cdot m^3 \cdot yr \cdot m^{-3}$

Results – Effect factor



Application to crop growing systems

Category impact	Tomato		Cucumber		Zucchini		Melon		Aubergine	
Unit	species·yr·kg^{-1}	%	species·yr·kg^{-1}	%	species·yr·kg^{-1}	%	species·yr·kg^{-1}	%	species·yr·kg^{-1}	%
Salinity impact due to water use	7.16 x10^{-13}	0.08	3.84 x10^{-13}	0.05	1.07 x10^{-12}	0.02	1.72 x10^{-12}	0.09	8.14E-13	0.02
Climate change	6.16 x10^{-10}	69.7	5.85 x10^{-10}	73.2	1.96 x10^{-9}	37.4	7.07 x10^{-10}	38.3	3.67 x10^{-9}	70.4
Terrestrial acidification	2.32 x10^{-12}	0.26	2.12 x10^{-12}	0.27	9.88 x10^{-12}	0.19	3.38 x10^{-12}	0.18	1.43 x10^{-11}	0.28
Freshwater eutrophication	3.85 x10^{-13}	0.04	3.46 x10^{-13}	0.04	5.63 x10^{-13}	0.01	3.82 x10^{-13}	0.02	2.56 x10^{-12}	0.05
Terrestrial ecotoxicity	2.40 x10^{-11}	2.71	2.10 x10^{-12}	0.26	4.73 x10^{-12}	0.09	3.08 x10^{-12}	0.17	7.38 x10^{-11}	1.42
Freshwater ecotoxicity	2.59 x10^{-14}	0.00	1.10 x10^{-14}	0.00	1.39 x10^{-13}	0.00	7.65 x10^{-14}	0.00	1.14 x10^{-13}	0.00
Marine ecotoxicity	1.21 x10^{-16}	0.00	4.86 x10^{-17}	0.00	1.86 x10^{-16}	0.00	8.28 x10^{-17}	0.00	5.33 x10^{-16}	0.00
Agricultural land occupation	2.15 x10^{-10}	24.4	1.82 x10^{-10}	22.7	3.12 x10^{-09}	59.5	1.08 x10^{-9}	58.5	1.25 x10^{-9}	24.1
Urban land occupation	8.11 x10^{-12}	0.92	1.29 x10^{-11}	1.61	4.48 x10^{-11}	0.86	2.18E x10^{-11}	1.18	7.62 x10^{-11}	1.46
Natural land transformation	1.68 x10^{-11}	1.90	1.52 x10^{-11}	1.90	9.87 x10^{-11}	1.88	2.72 x10^{-11}	1.47	1.20 x10^{-10}	2.30
Total	8.84 x10^{-10}	100	7.99 x10^{-10}	100	5.24 x10^{-9}	100	1.84 x10^{-9}	100	5.21 x10^{-9}	100

Potential future improvements

- Inclusion of more taxa

- Generalization to a global level to make it applicable for LCA

Impacts of water consumption on Human Health

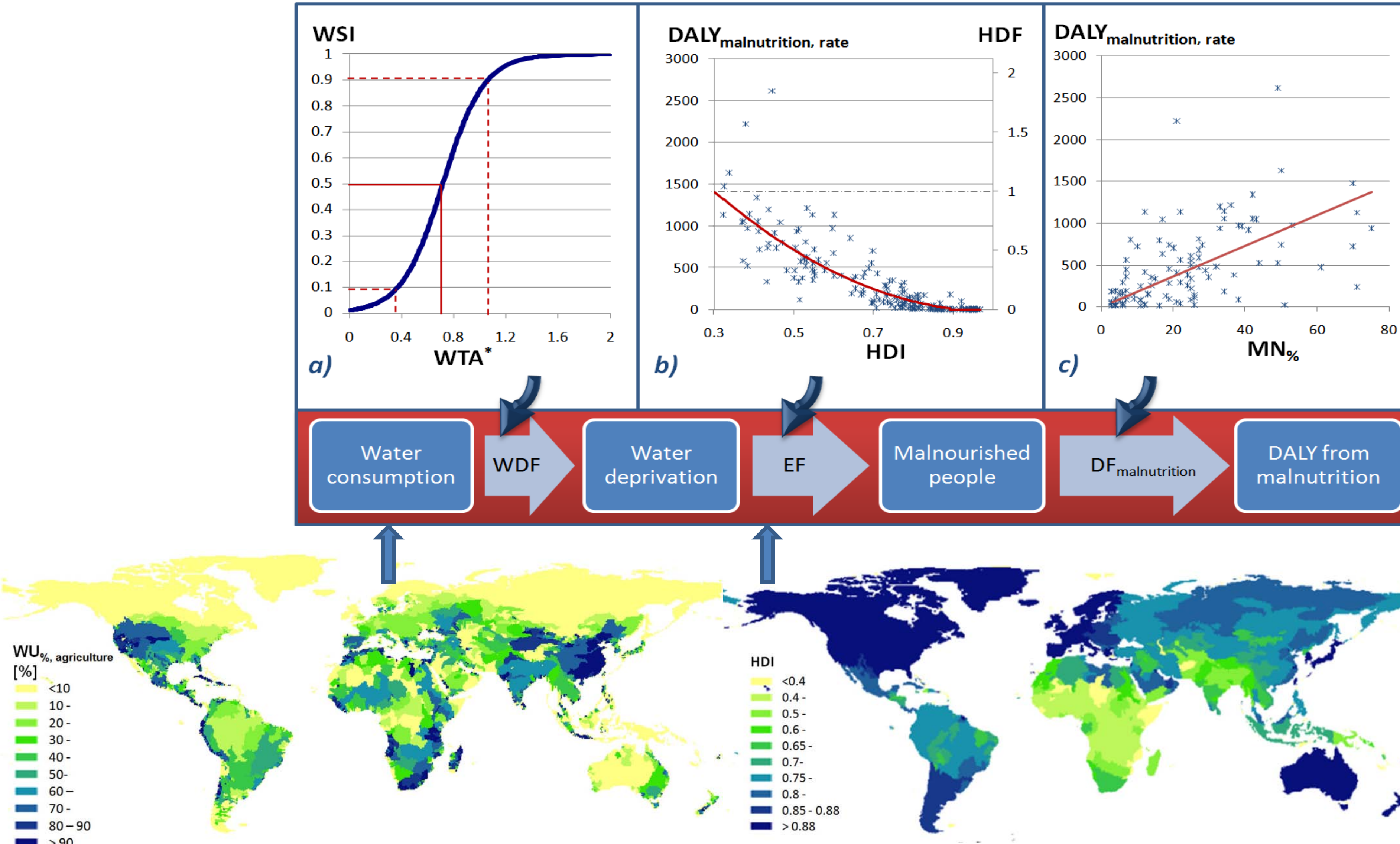
Pfister et al 2009: Impacts on human health

- Main pathway is malnutrition due to lack of freshwater and diminished agricultural yields

$$\Delta HH_{malnutrition,i} = \underbrace{\underbrace{WSI_i \cdot WU_{\%agriculture,i}}_{WDF_i} \cdot \underbrace{HDF_{malnutrition,i} \cdot WR_{malnutrition}^{-1}}_{EF_i} \cdot DF_{malnutrition}}_{CF_{malnutrition,i}} \cdot WU_{consumptive,i}$$

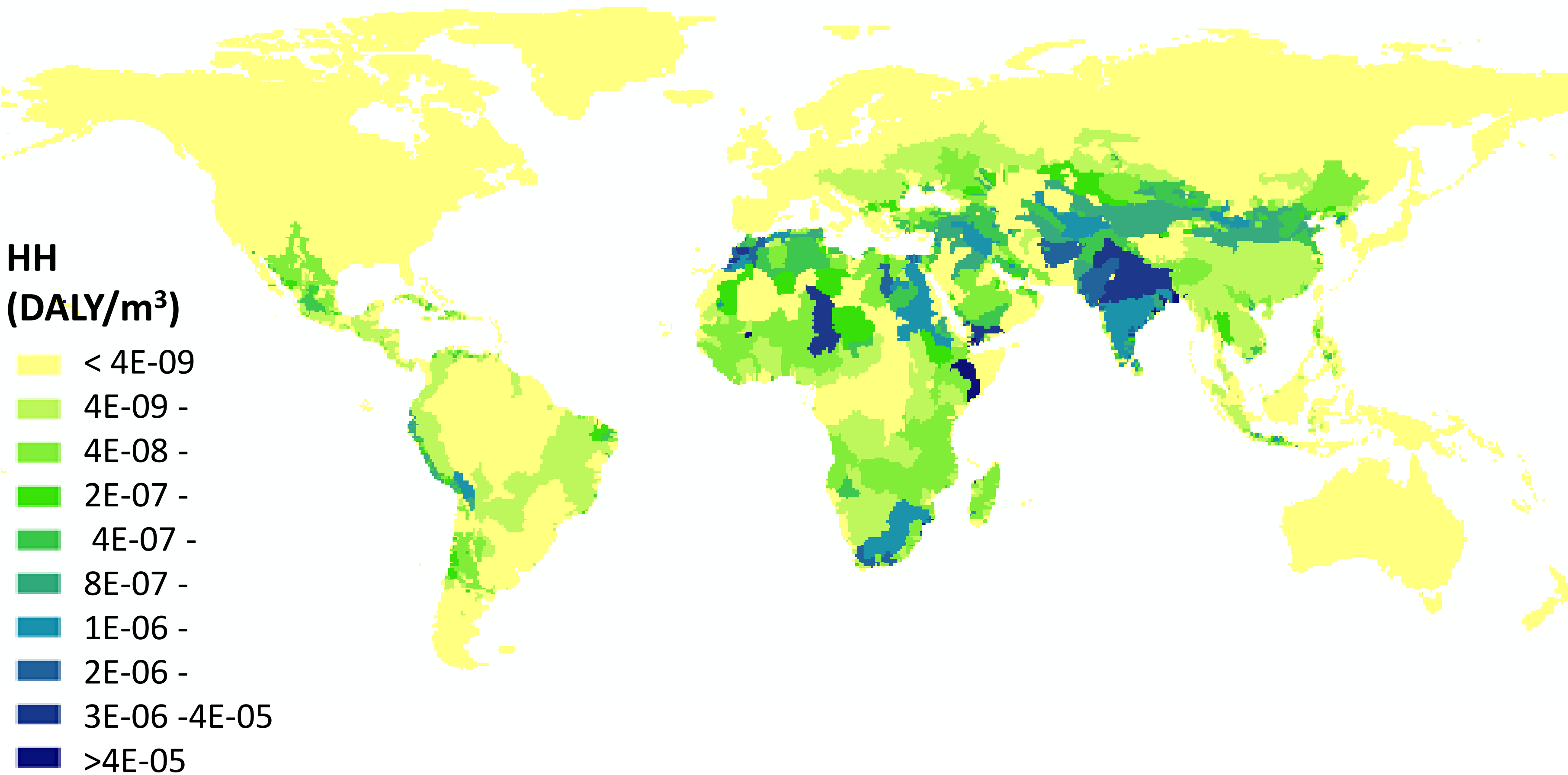
$HH_{malnutrition,\,i}$: human health damage (DALY)
WSI: physical water stress index (-)
$WU_{\%agriculture}$: fraction of agricultural water use (-)
WDF_i: water deprivation factor (m3 deprived/m3 consumed)
$HDF_{malnutrition,i}$: human development factor (-)
$WR_{malnutrition}$: per-capita water requirement to prevent malnutrition (m3/yr*capita)
EF_i: effect factor (capita *yr/m3 deprived) → Annual number of malnurished people per water quantity deprived
$DF_{malnutrition}$: damage factor (DALY/yr*capita) → Damage caused by malnutrition
$WU_{consumptive}$: consumptive water use (m3)
$CF_{malnutrition}$: specific damage per unit of water consumed (DALY/m3 consumed)

Pfister et al 2009: Impacts on human health



Pfister et al.(2009)

Pfister et al 2009: Impacts on human health



Pfister et al.(2009)

Summary of Uncertainties on watershed level

We assessed uncertainty using k as dispersion factors:

- Median * k results the 97.5% confidence interval
- Median / k results the 2.5% confidence interval

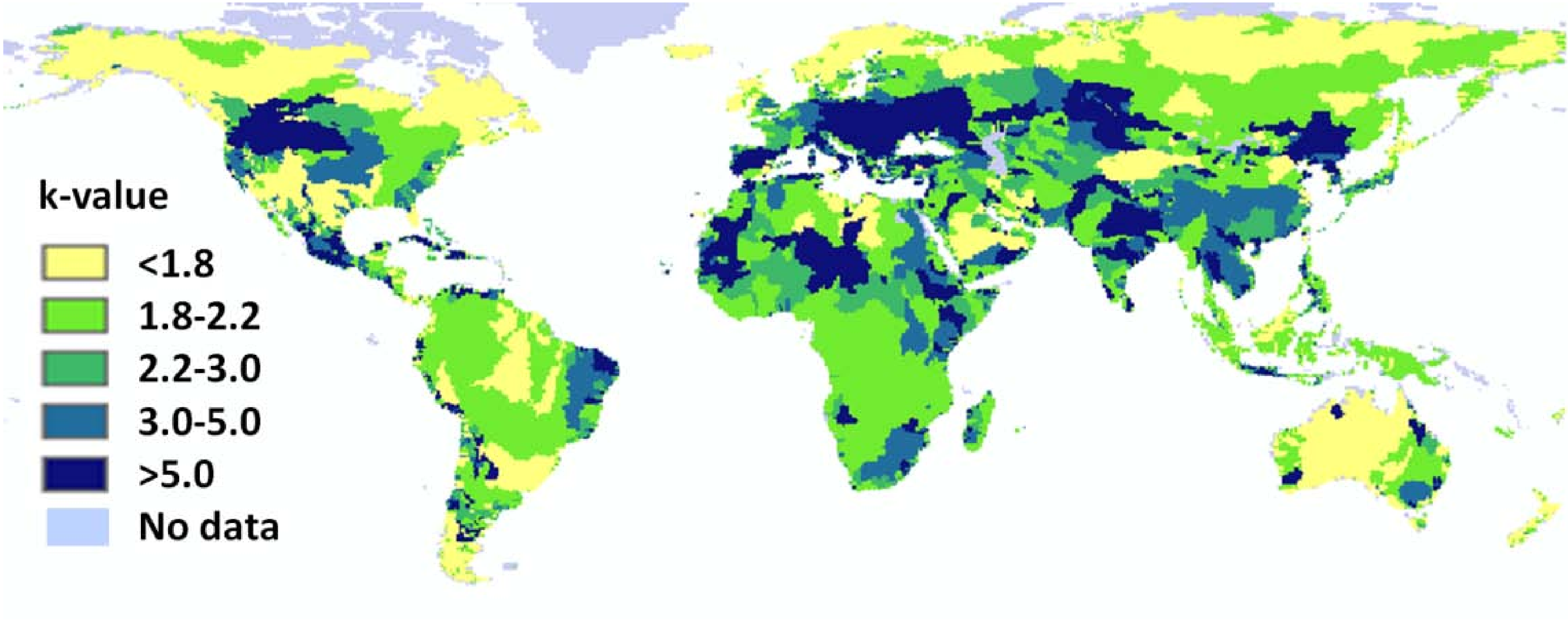
	k_{WSI}	K_{CF}
Average	2.76	18.14
Min	1.68	2.07
Max	12.20	571.22

Uncertainty levels until midpoint (WSI)

Impact assessment model step	Function	Parameters	k-value / Uncertainty function	Main source for uncertainty
Withdrawal to availability ratio (WTA)				
		Availability	GIS model	Based on Fekete et al. (2004)
		Withdrawals	HDI function	Based on Alcamo et al. (2003)
Water Stress Index (WSI)				
		VF-exponent	Binominal distribution (80/20%,)	Assumption of data accuracy
	WTA* function		VF	Precipitation distribution analysis
	WSI function		1.7	Assumption considering the logistic function

Details: http://www.ifu.ethz.ch/ESD/downloads/Uncertainty_water_LCIA.pdf

Related uncertainties: WSI



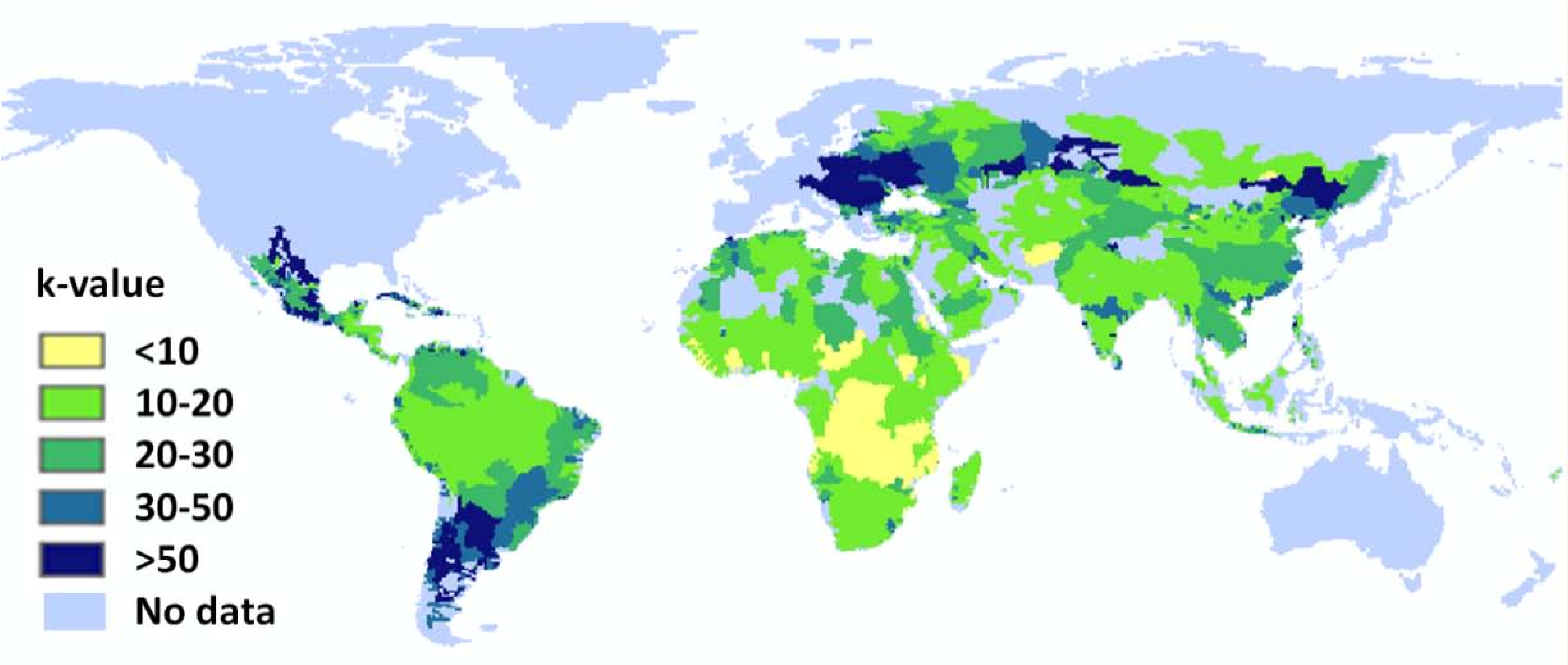
Uncertainty levels midpoint (WSI) to endpoint CF

Damage Assessment			
	Agricultural water use share	HDI function (See Annex)	Based on Alcamo et al. (2003)
	HDI values	1 .7-0.55 • H DI	Assumption based on HDI concept
	HDF function	4.83 (See Annex)	From analysis of HDF function
	Water requirements	3.0	Assumption based on correlation analysis
	Damage per case relation	2.0 (See Annex)	Based on continental damage reports (WHO 2007)

Details: http://www.ifu.ethz.ch/ESD/downloads/Uncertainty_water_LCIA.pdf

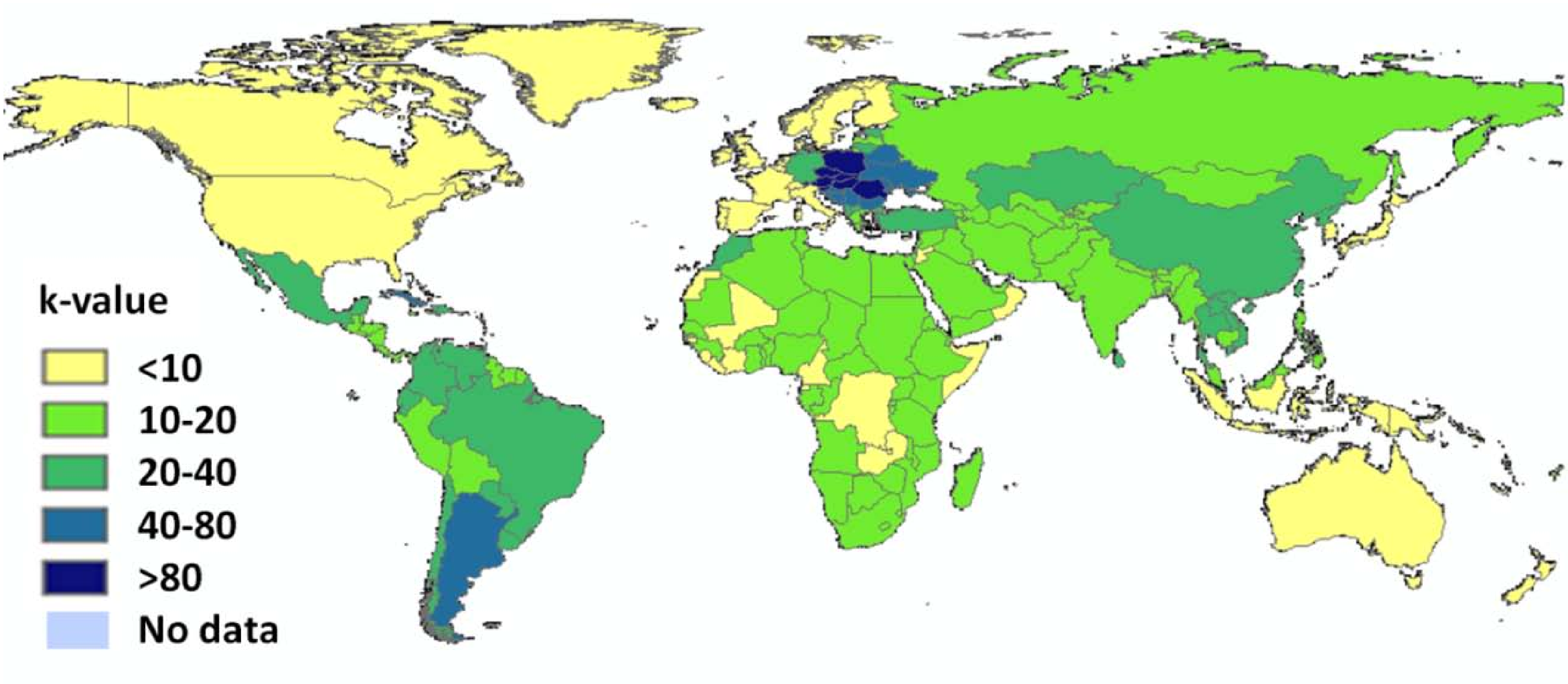
Endpoint CF uncertainty

k-value of endpoint characterization factors (CF) on watershed level.



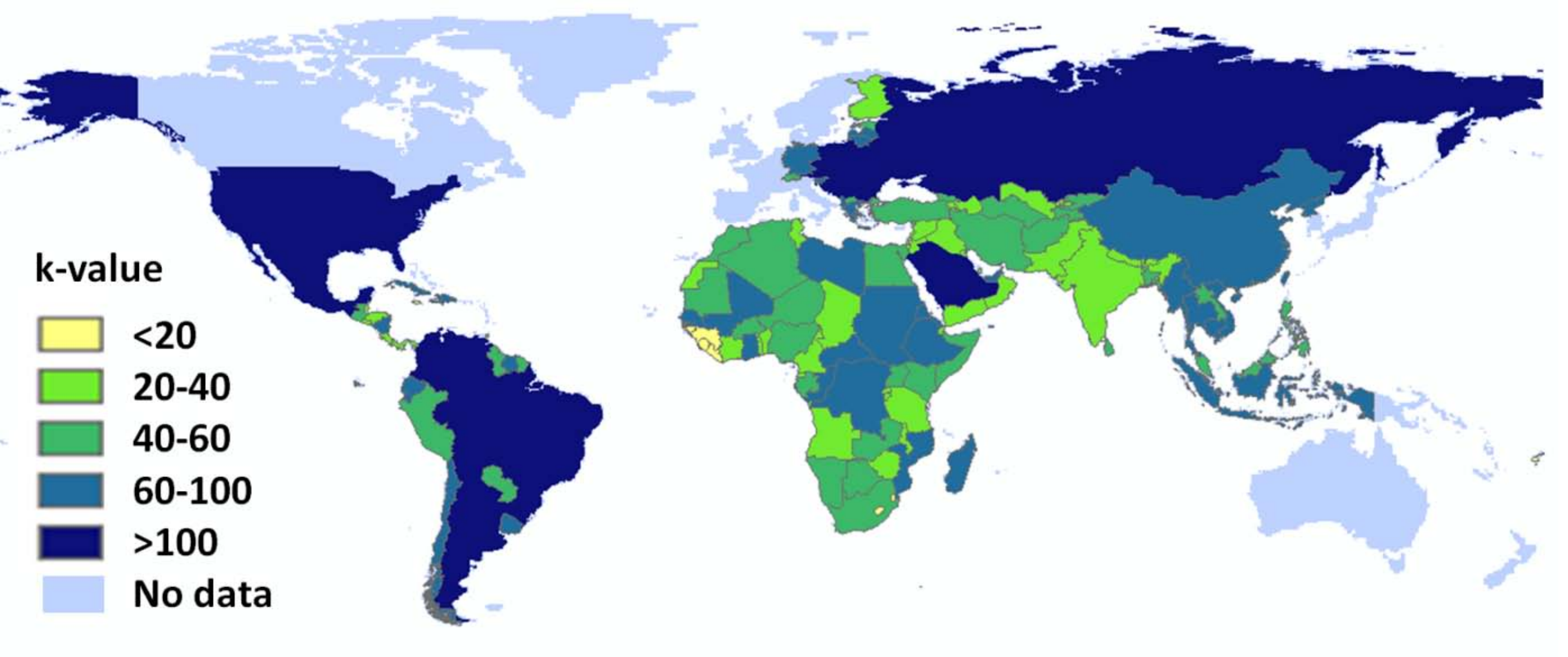
Uncertainty due to aggregation on country level (Variability)

k-value caused by the aggregation of watershed to country resolution for endpoint assessment



Country CF uncertainty (endpoint)

Total endpoint impact uncertainty on country resolution combining uncertainties of watershed model and due to aggregation.



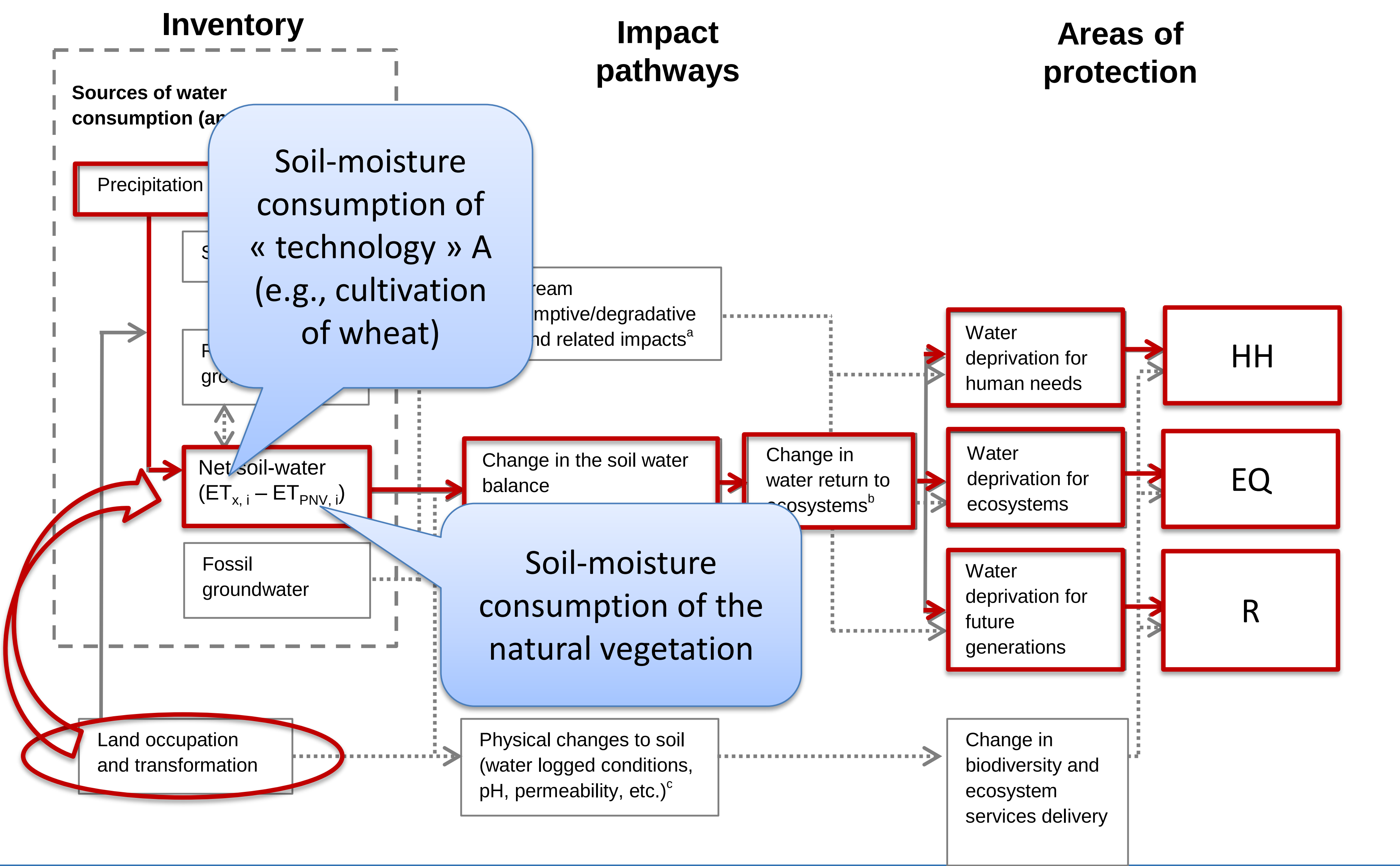
Potential future improvements

- Better hydrological models and water cosnumption data are required

- Further research on the cause-effect chain is necessary to decrease uncertainty

Green Water (Inventory method)

Soil-moisture use impact pathway



$NET_{soil\text{-}water} = \mathbf{ET_{x,\,\mathit{i}}} - ET_{PNV,i}$

- Soil-moisture consumption (mm/y=l/m^2y) under a specific human land use x (e.g., cultivation of wheat) at the location *i*
- **How to get $ET_{x,\,i}$?**
  1. It can be measured in-situ with lysimeters…
  2. …estimated following models…
  3. ...or approximated by adoption of figures from databases and from previous studies.

$NET_{soil\text{-}water} = ET_{x,i} - \mathbf{ET_{PNV,\mathit{i}}}$

- Evapotranspiration (mm/y=l/m^2y) of the natural reference system (i.e., PNV) at the location *i*
- **Two methods were combined to calculate it**:

Empirical approach

(Piñol et al. 1991)

$$ET_{PNV} = \left(\frac{\left(\frac{P_i}{ET_{0,i}}\right)^k}{1 + \left(\frac{P_i}{ET_{0,i}}\right)^k} \right)^{\frac{1}{k}} \times ET_{0,i}$$

$ET_{PNV,i} = f(ET_{0,i}, P_i, k)$, **only for dry lands**

k: local-dependent parameter.

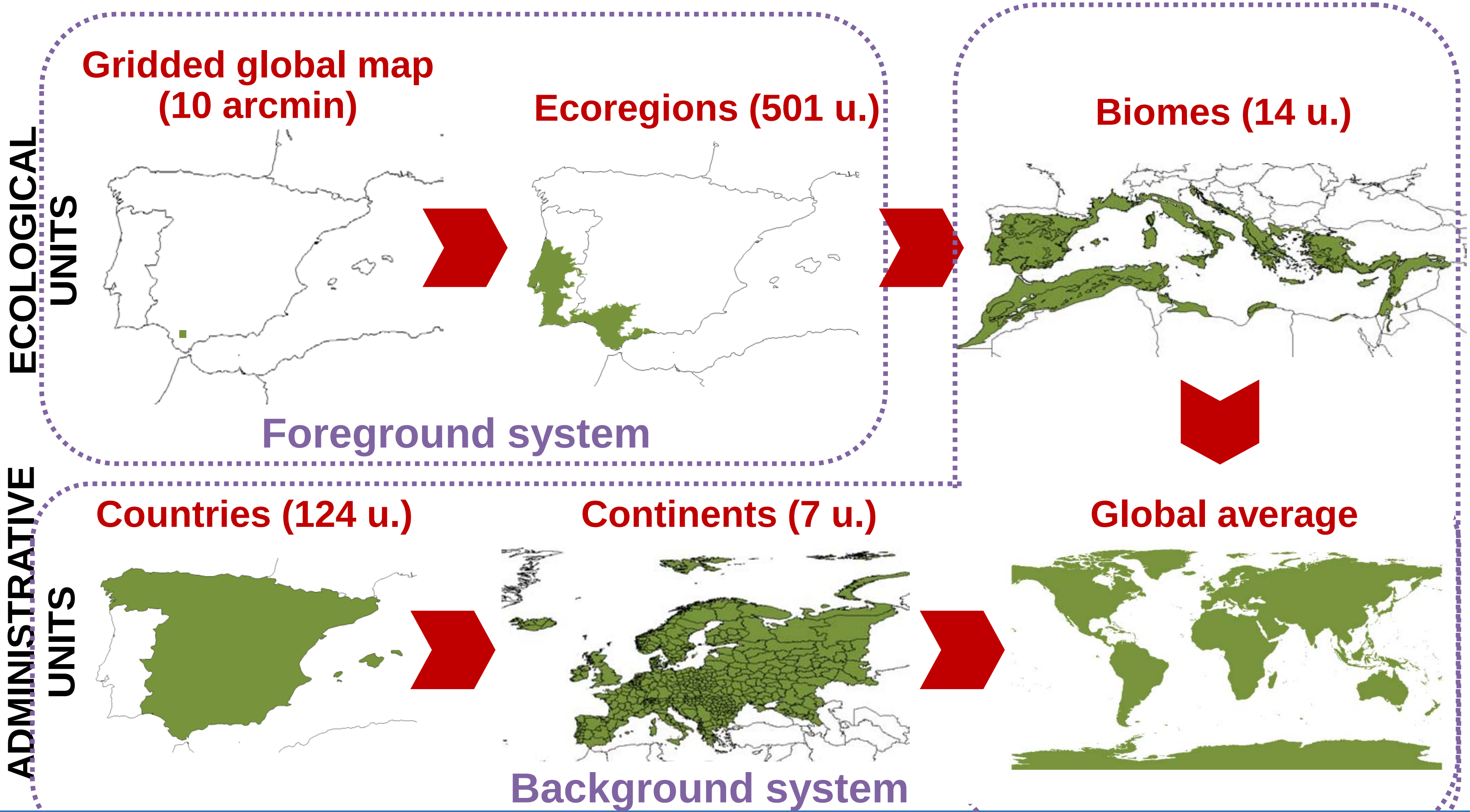
Unknown value: $1.03 \leq k \leq 2.40$

27 scenarios of $ET_{PNV,i}$ with 27 k *(k_j)*

Calibrated approach: $\mathbf{k_{opt,\mathit{i}} = k_\mathit{j}}$ **for min** $\left| \mathbf{ET_{PNV,\mathit{i}} - AET_i} \right|$

Spatial aggregation of $k_{opt,i}$ & $ET_{PNV,i}$

Spatial aggregation is essential to make values usable in LCA



Potential future improvements

- Better models and actual and reference evapotranspiration are required
- Further research on linking soil-moisture water consumption to the described characterization models is needed (e.g. distinction of gorund and surface water effect).

References

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