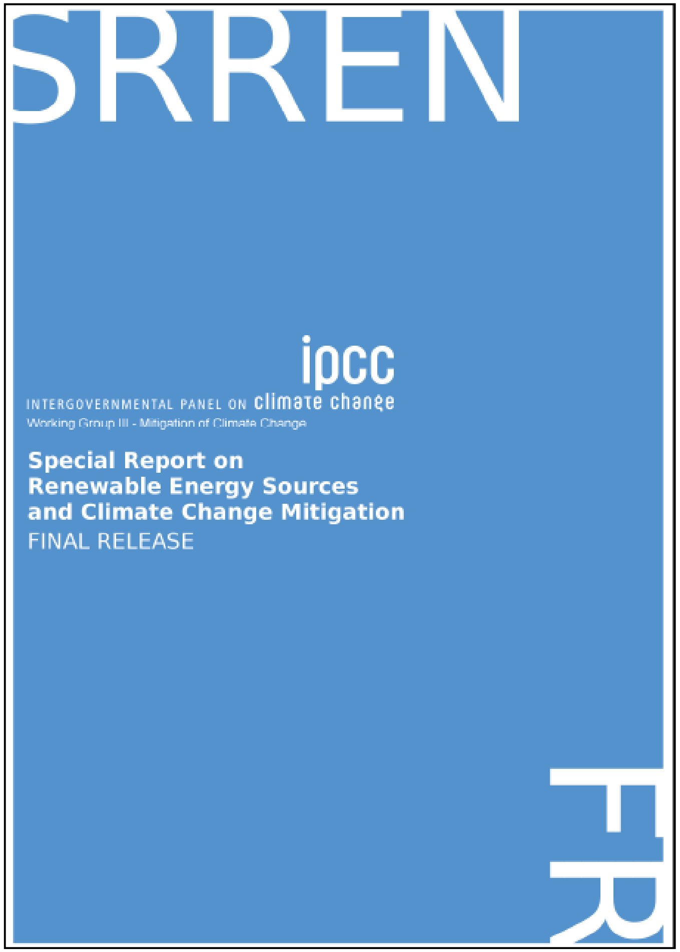
Water consumption from hydropower production

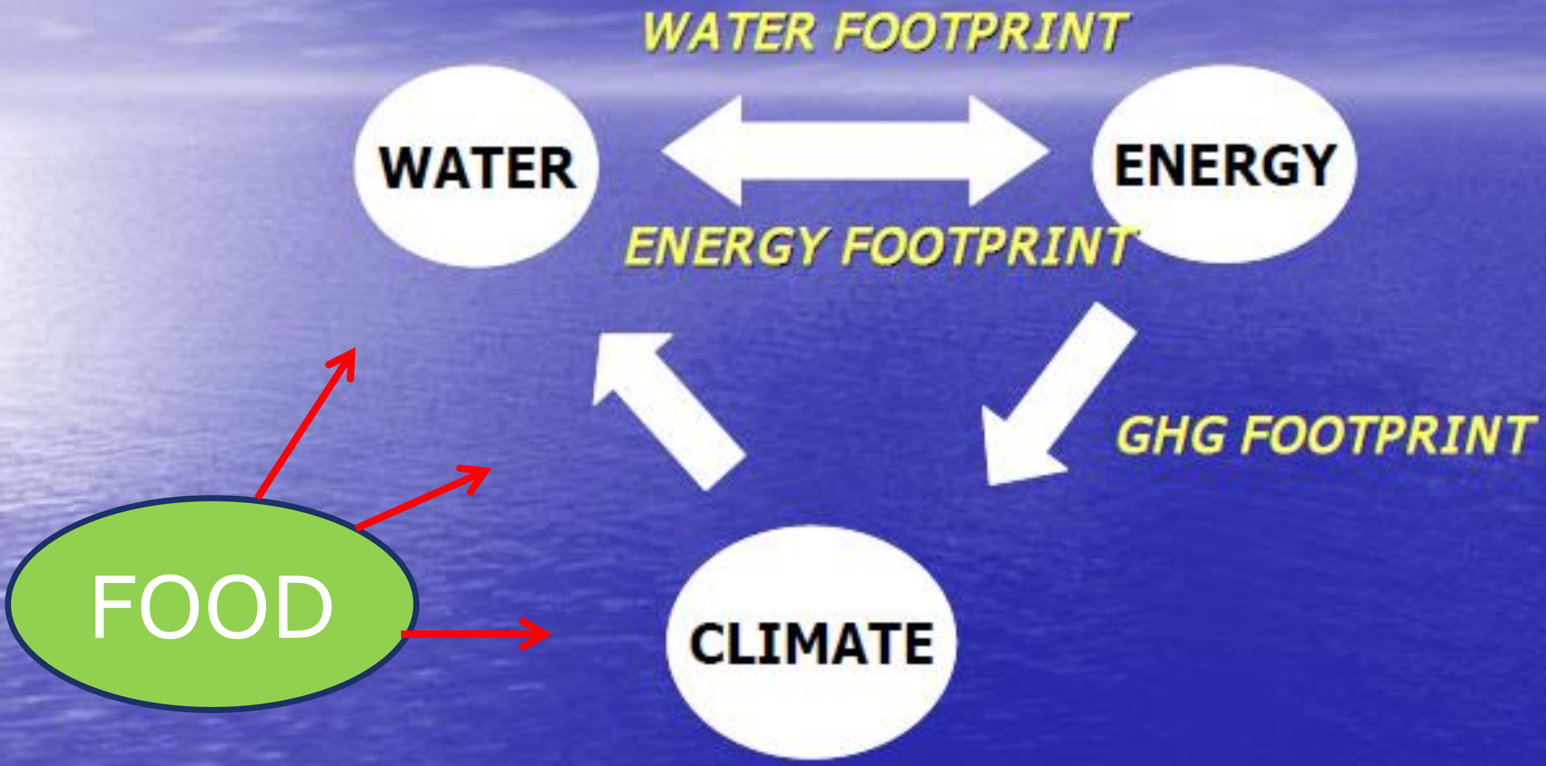
Water consumption - what raised the attention?



IPCC Special Report on Renewable Energy (2011):

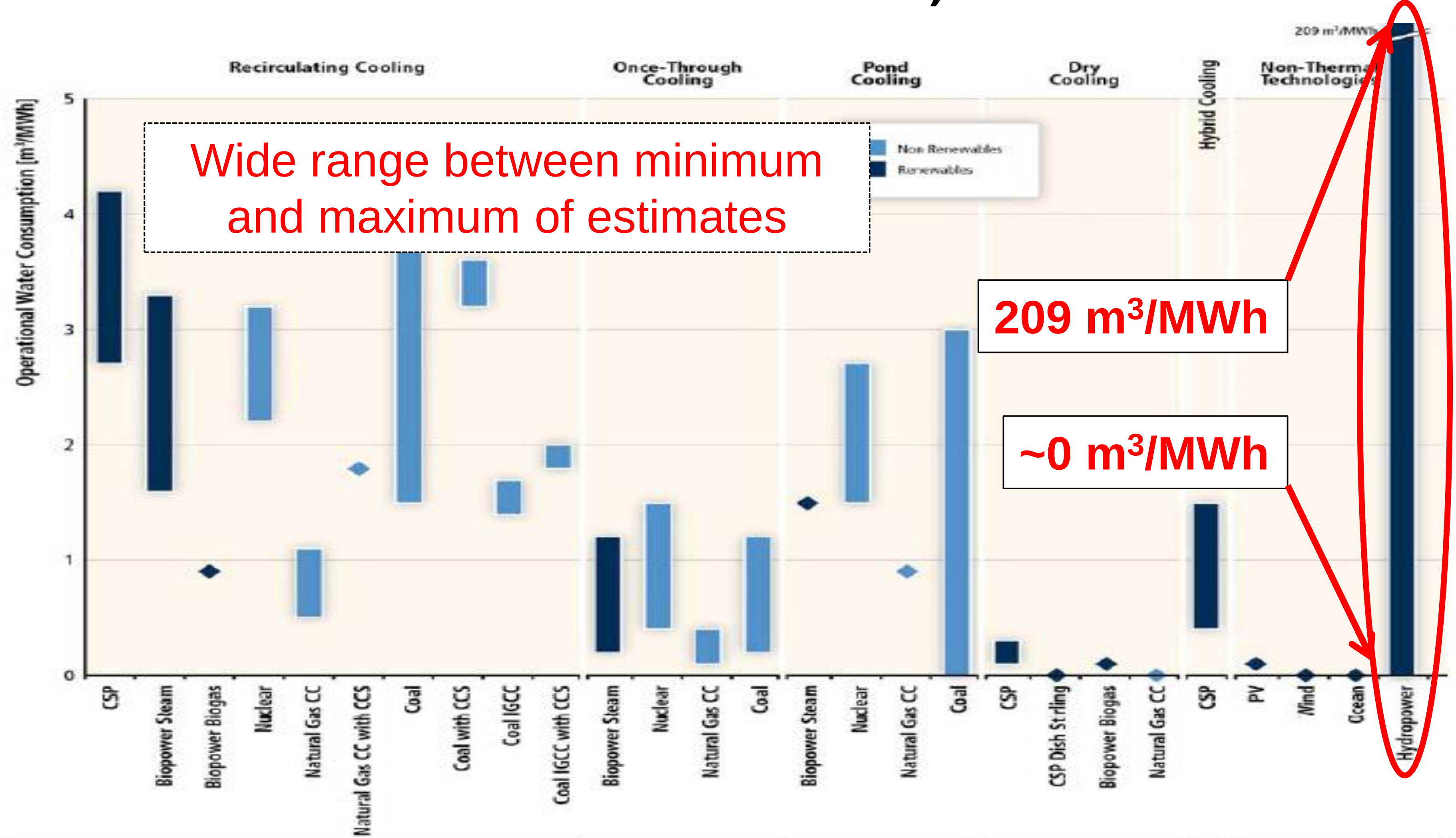
- What is the potential for renewable sources to replace fossil-based fuels?
  Lenke mal
- The different technologies benchmarked with respect to various criteria, including ‘water needed to produced 1 MWh electricity (*water consumption*)’

Water => energy => GHG footprints



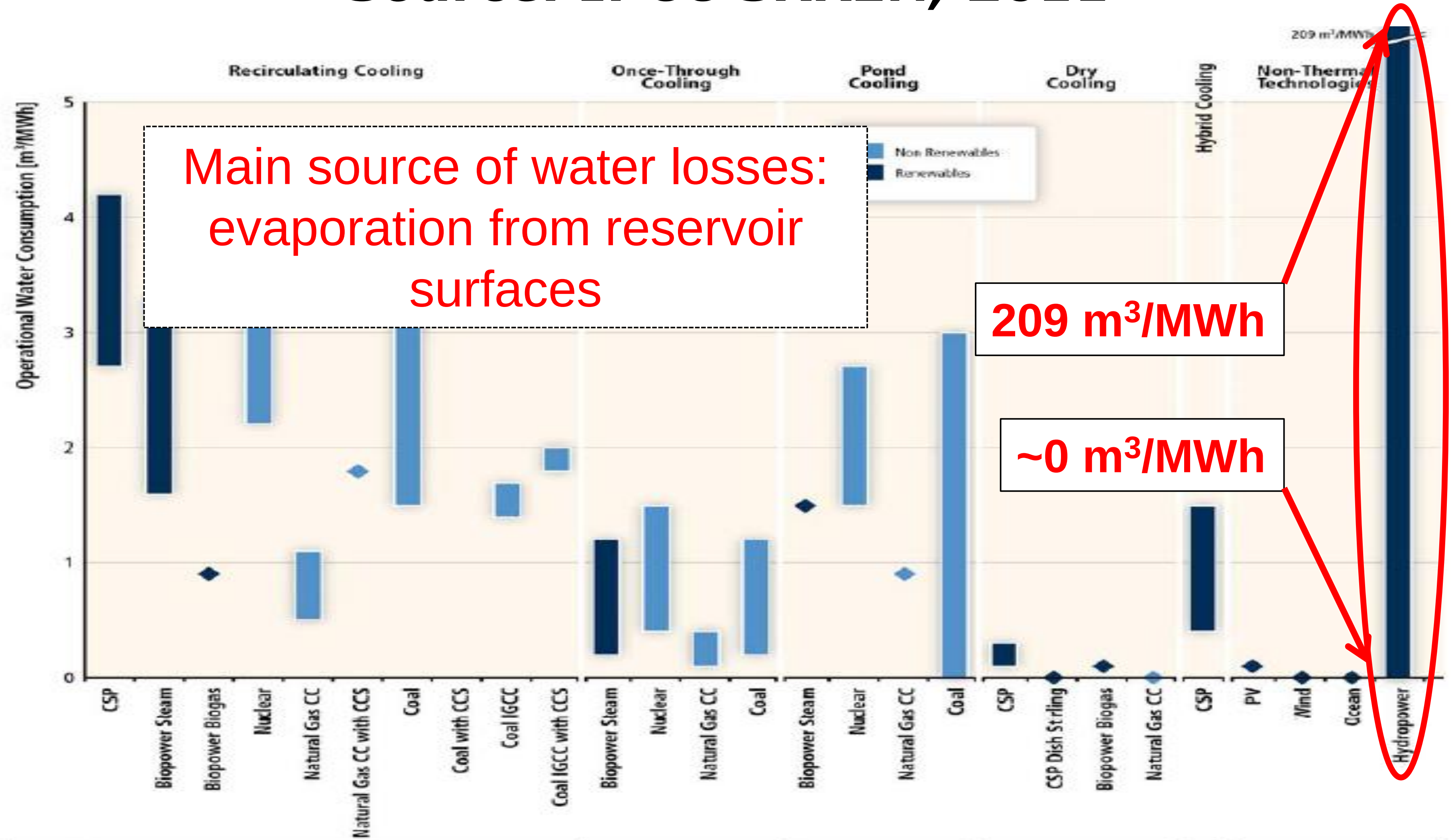
- an inter-related system!

Water consumption from electricity generation: *Source: IPCC SRREN, 2011*



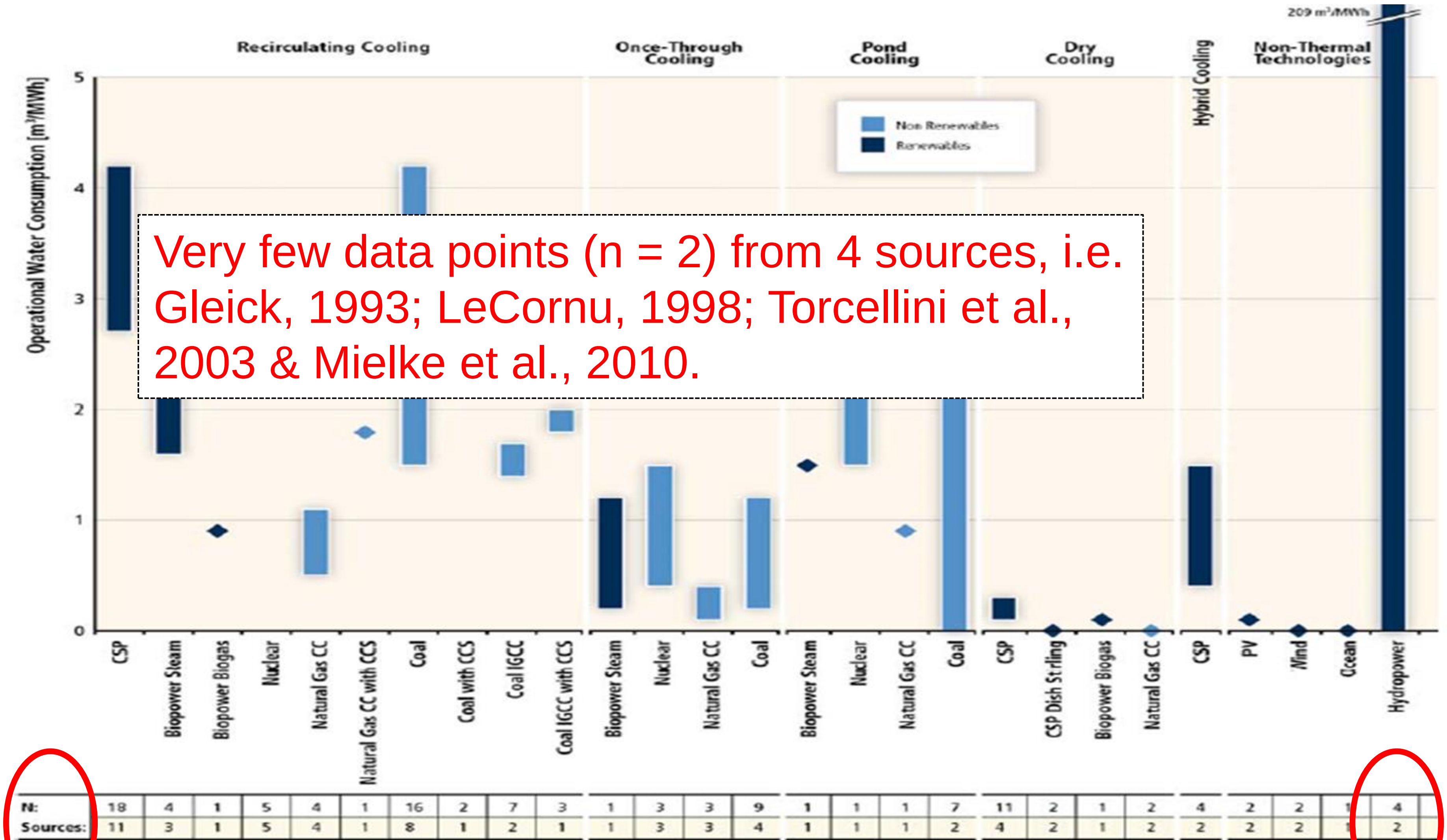
	CSP	Biopower Steam	Biopower Biogas	Nuclear	Natural Gas CC	Natural Gas CC with CCS	Coal	Coal with CCS	Coal IGCC	Coal IGCC with CCS	Biopower Steam	Nuclear	Natural Gas CC	Coal	Biopower Steam	Nuclear	Natural Gas CC	Coal	CSP	CSP Dish Stirling	Biopower Biogas	Natural Gas CC	CSP	PV	Wind	Ocean	Hydropower
N:	18	4	1	5	4	1	16	2	7	3	1	3	3	9	1	1	1	7	11	2	1	2	4	2	2	1	4
Sources:	11	3	1	5	4	1	8	1	2	1	1	3	3	4	1	1	1	2	4	2	1	2	2	2	2	1	2

Water consumption from electricity generation*:*
Source: IPCC SRREN, 2011



N:	18	4	1	5	4	1	16	2	7	3	1	3	3	9	1	1	1	7	11	2	1	2	4	2	2	1	4
Sources:	11	3	1	5	4	1	8	1	2	1	1	3	3	4	1	1	1	2	4	2	1	2	2	2	2	1	2

Water consumption from electricity generation: *Source: IPCC SRREN, 2011*



Very few data points (n = 2) from 4 sources, i.e. Gleick, 1993; LeCornu, 1998; Torcellini et al., 2003 & Mielke et al., 2010.

IPCC SRREN (2011) states

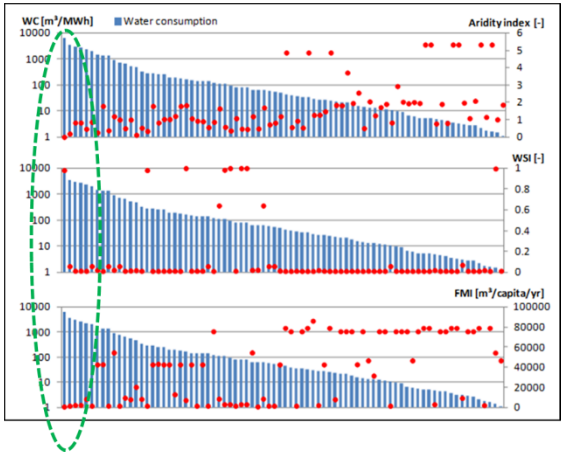
- *Upper values for hydropower result from few studies measuring gross evaporation values, and may not be representative.*

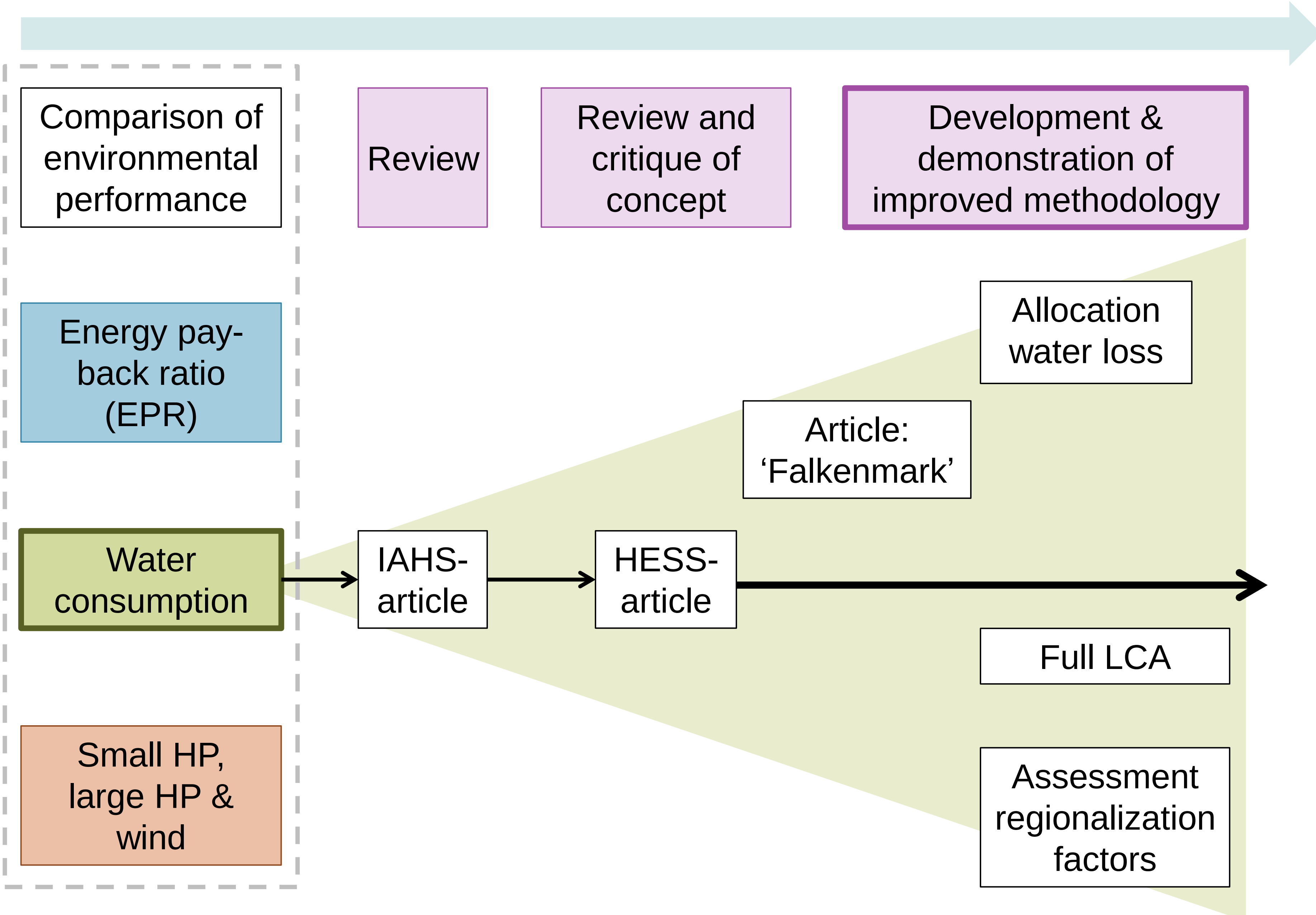
- *Research may be needed to determine the net effect of reservoir construction on the evaporation in the specific watershed.*

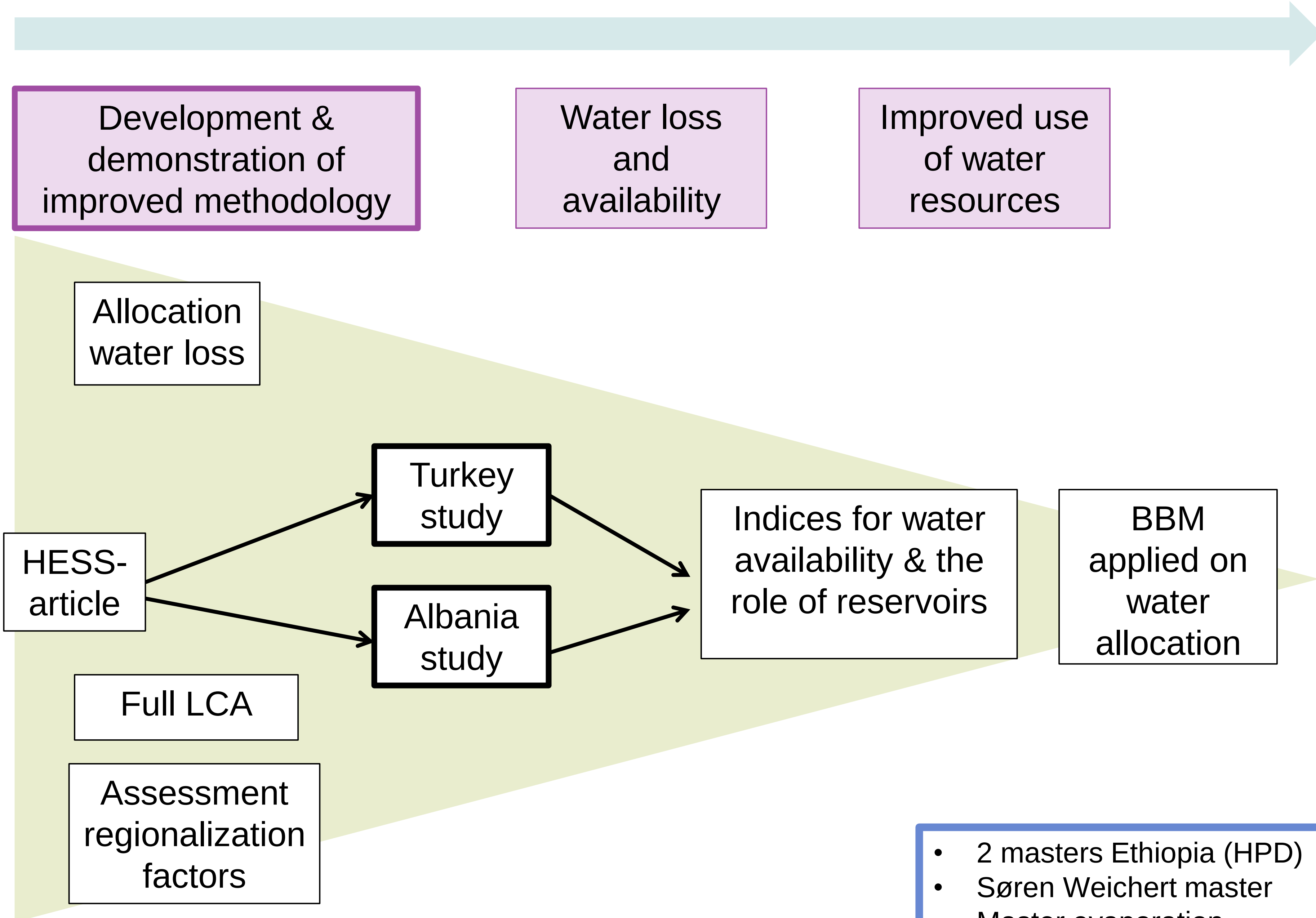
- *Allocation schemes for determining water consumption from various reservoir uses in the case of multipurpose reservoirs can significantly influence reported water consumption values.*

On-going scientific debate

- Bakken et al. (2013) claims the methodological framework is immature and presents a biased picture. Has received support from e.g. Demeke et al. (2013), Chenoweth et al. (2014).
- Some claim hydropower production is globally a large water consumer, e.g. Gerbens-Lenes (2009), Mekonnen and Hoekstra (2012), Liu et al. (2015).
- High water consumption values can be observed in water-stressed regions, but this is also where the reservoirs are most needed (Weichert, 2013).
- Reservoirs are needed to mitigate the effects of climate change on the water resources (e.g. IPCC, 2008)




Comparison of environmental performance
Review
Review and critique of concept
Development & demonstration of improved methodology
Energy pay-back ratio (EPR)
Allocation water loss
Article: ‘Falkenmark’
Water consumption
IAHS-article
HESS-article
Full LCA
Small HP, large HP & wind
Assessment regionalization factors



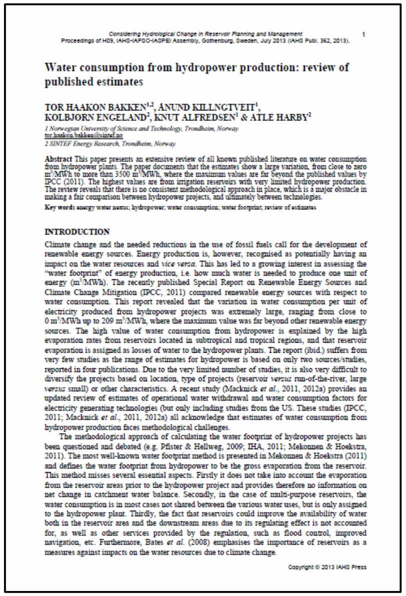
- 2 masters Ethiopia (HPD)
- Søren Weichert master
- Master evaporation
- UiO's work
- SINTEF report

Highlights - results

Results from our review documented in:

1

Proceedings of H09, IAHS-IAPSO-IASPEI Assembly, Gothenburg, Sweden, July 2013 (IAHS Publ. 362, 2013).



Considering Hydrological Change in Reservoir Planning and Management 1
Proceedings of H09, IAHS-IAPSO-IASPEI Assembly, Gothenburg, Sweden, July 2013 (IAHS Publ. 362, 2013).

Water consumption from hydropower production: review of published estimates

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Abstract This paper presents an extensive review of all known published literature on water consumption from hydropower plants. The paper documents that the estimates show a large variation, from close to zero m^3/MWh to more than 3500 m^3/MWh, where the maximum values are far beyond the published values by IPCC (2011). The highest values are from irrigation reservoirs with very limited hydropower production. The review reveals that there is no consistent methodological approach in place, which is a major obstacle in making a fair comparison between hydropower projects, and ultimately between technologies.

Key words energy water nexus; hydropower; water consumption; water footprint; review of estimates

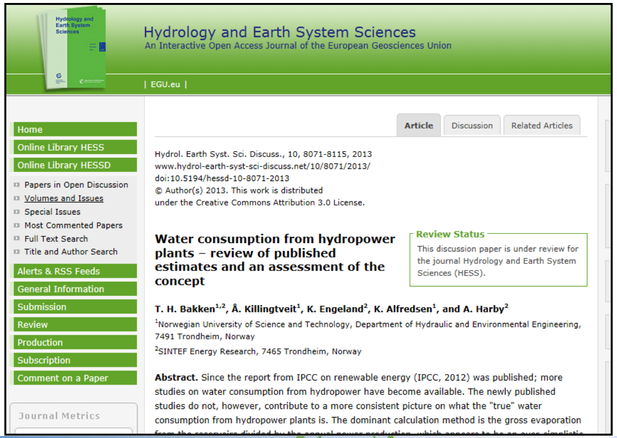
INTRODUCTION

Climate change and the needed reductions in the use of fossil fuels call for the development of renewable energy sources. Energy production is, however, recognised as potentially having an impact on the water resources and *vice versa*. This has led to a growing interest in assessing the "water footprint" of energy production, i.e. how much water is needed to produce one unit of energy (m^3/MWh). The recently published Special Report on Renewable Energy Sources and Climate Change Mitigation (IPCC, 2011) compared renewable energy sources with respect to water consumption. This report revealed that the variation in water consumption per unit of electricity produced from hydropower projects was extremely large, ranging from close to 0 m^3/MWh up to 209 m^3/MWh, where the maximum value was far beyond other renewable energy sources. The high value of water consumption from hydropower is explained by the high evaporation rates from reservoirs located in subtropical and tropical regions, and that reservoir evaporation is assigned as losses of water to the hydropower plants. The report (ibid.) suffers from very few studies as the range of estimates for hydropower is based on only two sources/studies, reported in four publications. Due to the very limited number of studies, it is also very difficult to diversify the projects based on location, type of projects (reservoir *versus* run-of-the-river, large *versus* small) or other characteristics. A recent study (Macknick *et al.*, 2011, 2012a) provides an updated review of estimates of operational water withdrawal and water consumption factors for electricity generating technologies (but only including studies from the US. These studies (IPCC, 2011; Macknick *et al.*, 2011, 2012a) all acknowledge that estimates of water consumption from hydropower production faces methodological challenges.

The methodological approach of calculating the water footprint of hydropower projects has been questioned and debated (e.g. Pfister & Hellweg, 2009; IHA, 2011; Mekonnen & Hoekstra, 2011). The most well-known water footprint method is presented in Mekonnen & Hoekstra (2011) and defines the water footprint from hydropower to be the gross evaporation from the reservoir. This method misses several essential aspects. Firstly it does not take into account the evaporation from the reservoir areas prior to the hydropower project and provides therefore no information on net change in catchment water balance. Secondly, in the case of multi-purpose reservoirs, the water consumption is in most cases not shared between the various water uses, but is only assigned to the hydropower plant. Thirdly, the fact that reservoirs could improve the availability of water both in the reservoir area and the downstream areas due to its regulating effect is not accounted for, as well as other services provided by the regulation, such as flood control, improved navigation, etc. Furthermore, Bates *et al.* (2008) emphasises the importance of reservoirs as a measures against impacts on the water resources due to climate change.

2

Hydrology and Earth System Sciences (2013)



Hydrol. Earth Syst. Sci. Discuss., 10, 8071-8115, 2013
www.hydrol-earth-syst-sci-discuss.net/10/8071/2013/
doi:10.5194/hessd-10-8071-2013
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Water consumption from hydropower plants – review of published estimates and an assessment of the concept

Review Status
This discussion paper is under review for the journal Hydrology and Earth System Sciences (HESS).

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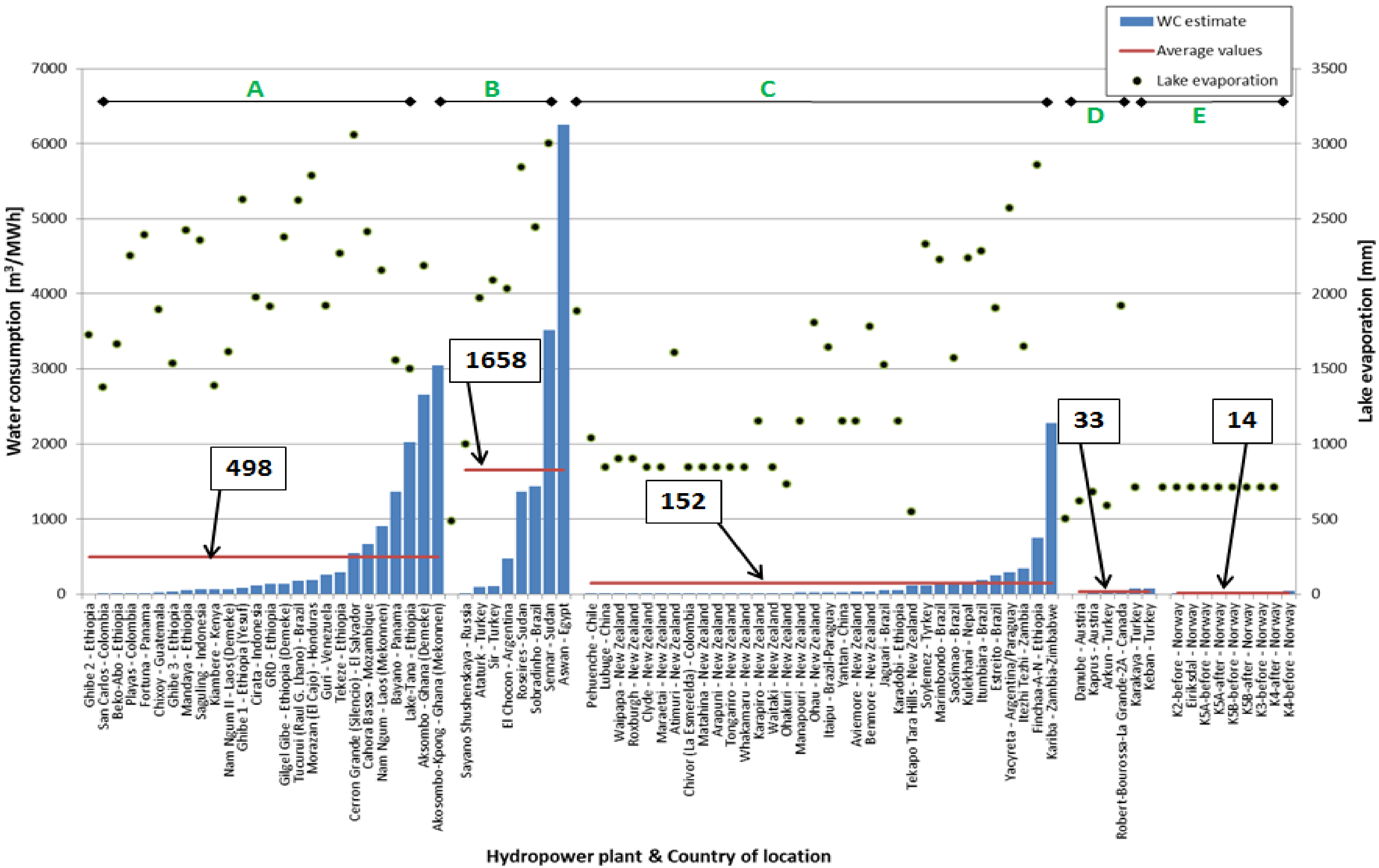
Abstract. Since the report from IPCC on renewable energy (IPCC, 2012) was published; more studies on water consumption from hydropower have become available. The newly published studies do not, however, contribute to a more consistent picture on what the "true" water consumption from hydropower plants is. The dominant calculation method is the gross evaporation

Single-plant studies – Gross values



Findings from our review of published values

- The presented estimates are based on different methodological approach. The dominating approach is the gross evaporation divided on production.
- Some of the newly published estimates are far beyond the earlier published maximum values by IPCC (2011).
- Only three studies report both gross and net evaporation. In these cases the net evaporation was 10-60 % of gross evaporation (water consumption).
- Some studies are single-plant studies, while others have a very large geographical extent, 'smoothening out' large variations in water consumption values.
- "No way" around the fact that HP has a large water consumption in some regions, given the current approach (gross evaporation) of calculating water consumption/footprint.

Critique: Methodological problems

1. Values are given as gross evaporation from the reservoir area. For dams constructed on desert land, the net evaporation will be equal to the gross values, but in most cases evaporation will be less, especially for dams in wetland areas and areas with vegetation where the net increase may be very limited.

2. Water stored in reservoirs is often used for multiple purposes; thus the evaporation losses should not all be assigned to the hydropower production.

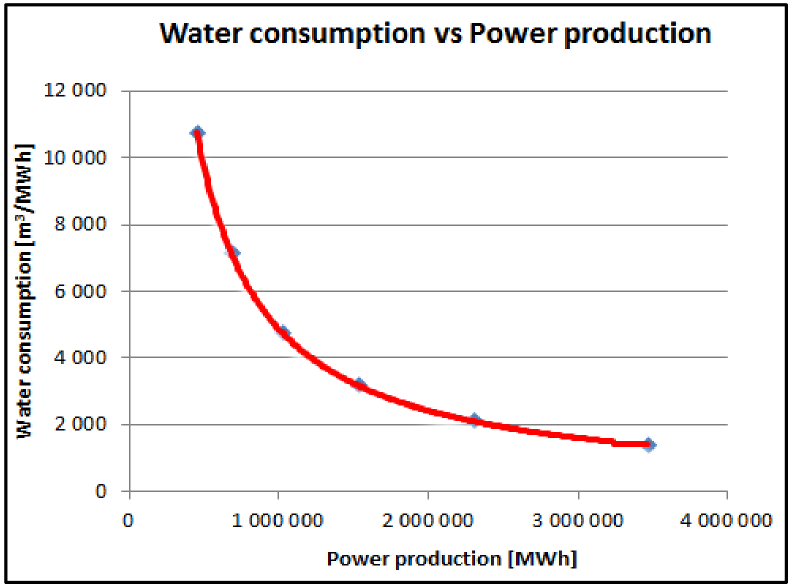
3. Impacts from the water consumption/footprint is ‘ignored’.

4. Construction of dams is a very common way to improve the availability of/access to water. Are reservoirs in arid regions not feasible due to high water footprints?

Critique: Methodological problems (2/3)

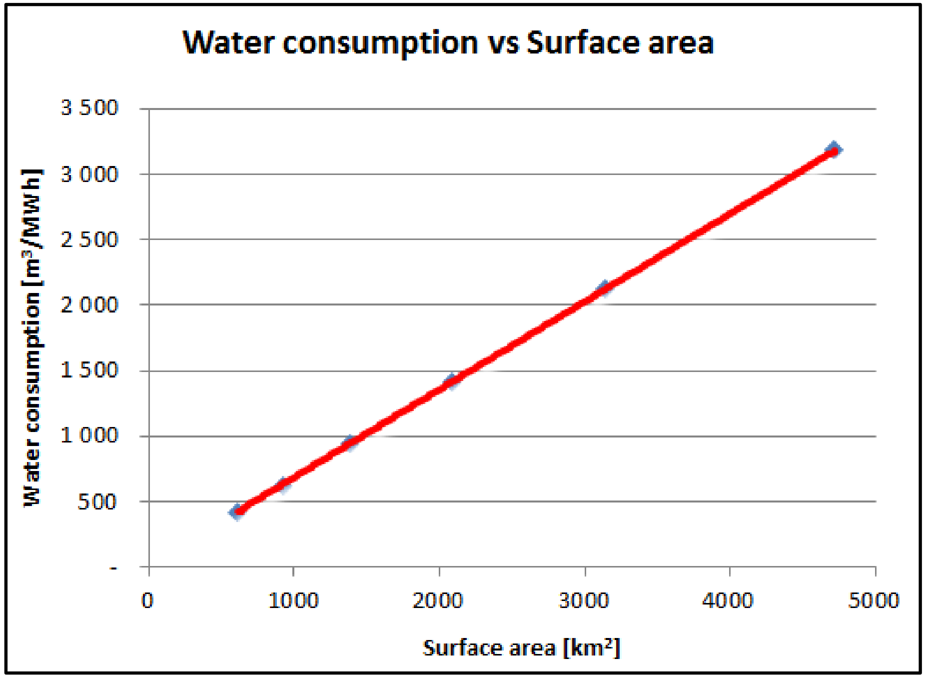
5. How to set the right system boundaries in space and time?

   - One reservoir might serve several hydropower plants
   - The production might vary a lot during the year and from year to year – what is the temporal resolution and span?



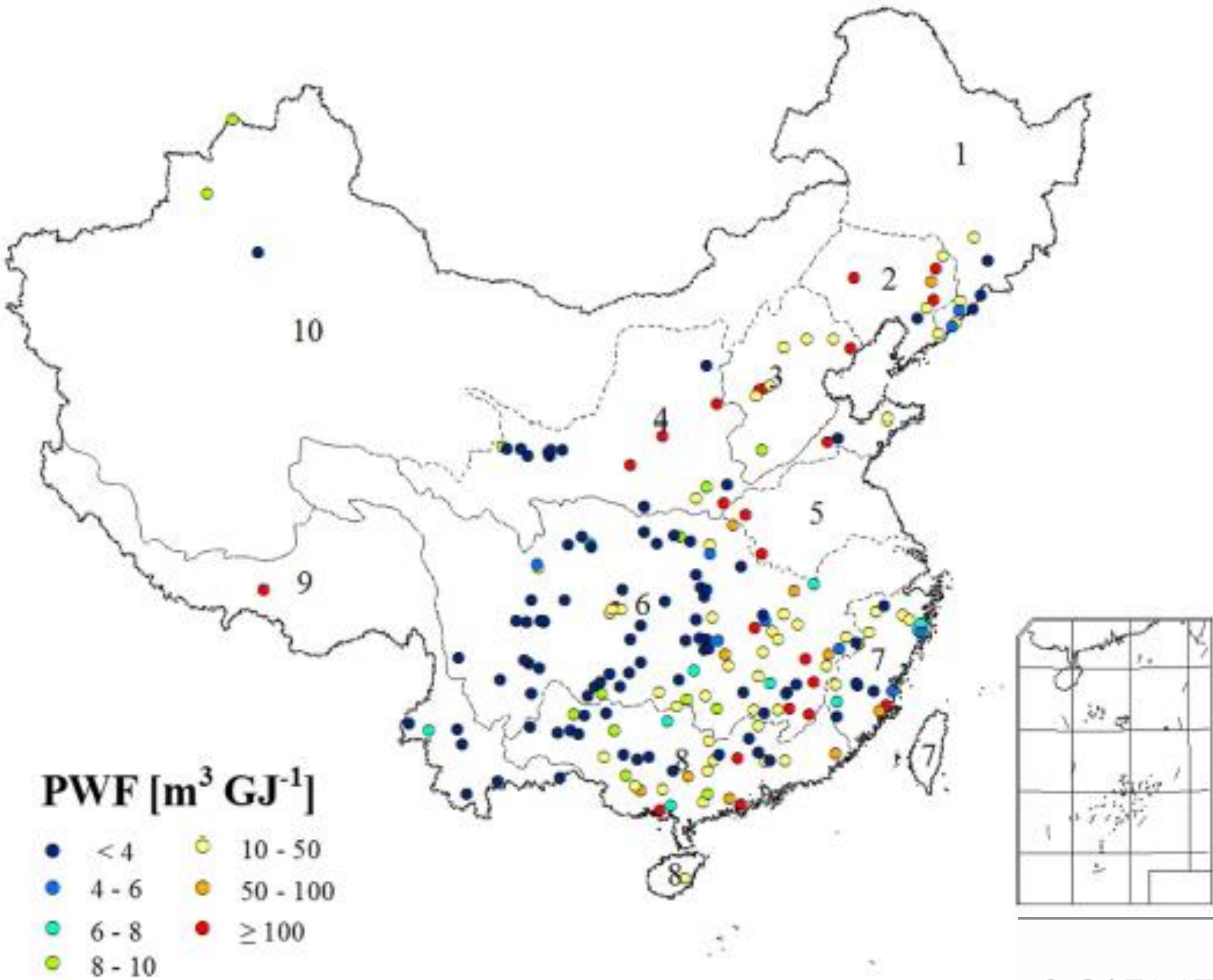
Critique: Methodological problems (3/3)

6. What about the use of existing lakes as reservoirs – should all evaporation losses be assigned to the hydropower production?



7. Withdrawal versus consumption?

Recent study in China – Product water footprint of hydropower



Source:
Liu et al., 2015


www.nature.com/scientificreports

SCIENTIFIC REPORTS

OPEN China's rising hydropower demand challenges water sector

Junguo Liu[1], Dandan Zhao[1], P.W. Gerbens-Leenes[2] & Dabo Guan[3]

Study area	Hydroelectric PWF [$m^3\ GJ^{-1}$]	Hydroelectric PWF [$m^3\ MWh^{-1}$]
United States average[40]	4.7	17
United States average – 120 largest plants[25]	19	68
Arizona, United States[26]	31.6	113.9
California, United States[41,42]	Min: 0.01 Median: 1.5 Max.: 58	Min: 0.04 Median: 5.4 Max.: 209
California[29]	Mean: 1.5	Mean: 5.4
	Median: 7.2	Median: 26
"All plants" in Northern New Zealand[7]	6.1	21.8
Norway[43]	1–1.2	3.8–4.4
Ethiopia Omo-Ghibe River[44]	Min.: 9.4	Min.: 34
	Max: 22.7	Max: 82
Ethiopia (Blue Nile)[45]	Min.: 3.1	Min.: 11
	Mean: 27.5	
	Max.: 38	
Sudan Roseires and Sennar irrigation reservoirs[46]	Min.: 381 Mean: 411 Max.: 978	Min.: 1371 Max.: 3521
Austria, Ethiopia, Turkey, Ghana, Egypt and PDR Laos[46]	Max.:1736	Max.: 6250
Global average[4]	22	80
Worldwide, 35 plants[5]	Min.: 0.3	Min.: 1.08
	Mean: 68	Mean: 244.8
	Max.: 846	Max.: 3045.6
China from this study	Min.: 0.001	Min.: 0.0036
	Mean: 3.6	Mean: 13
	Max.: 4234	Max.: 15244

Table 2. Comparison of hydroelectric product water footprints (PWF) estimated in the present study with previous values of Bakken *et al.*[17]. Note: In this table, the hydroelectric PWF is presented based on the same definition (i.e., the evaporative water consumption for each unit of hydropower generation). Values in $m^3\ MWh^{-1}$ were calculated by multiplying the values in $m^3\ GJ^{-1}$ by 3.6 (the conversion factor).

IPCC

Min: 0.04 Median: 5.4 Max.: 209

Max values very high!

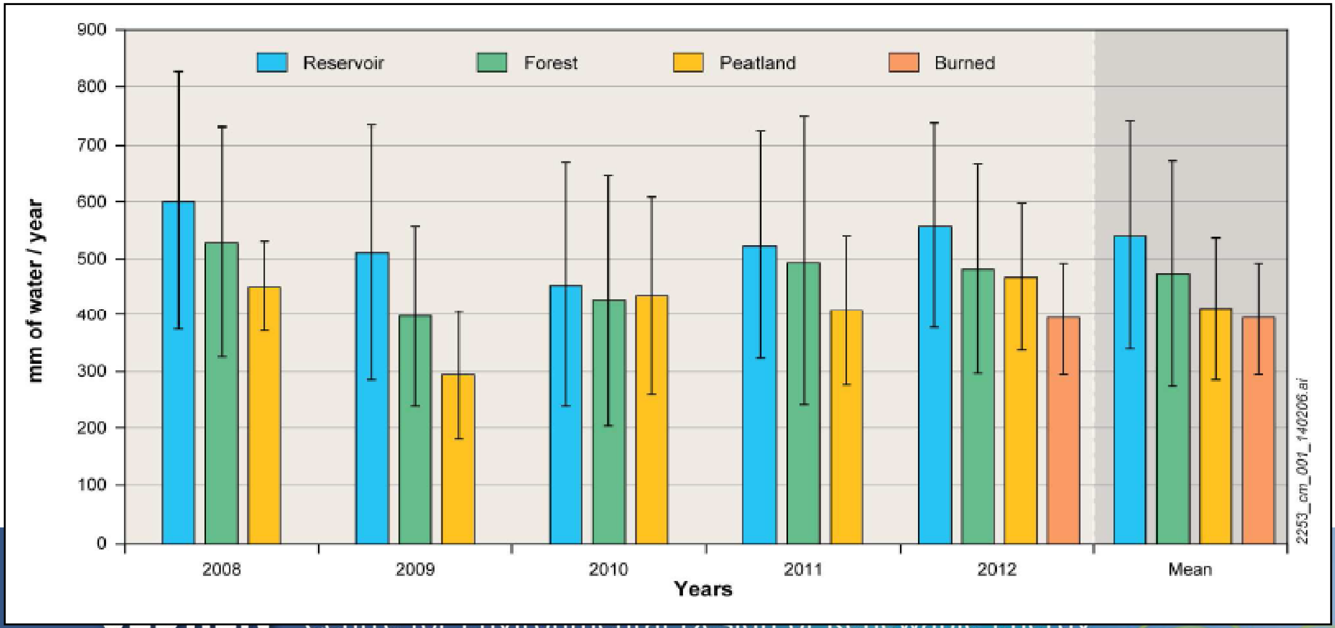
Min.: 0.0036
Mean: 13
Max.: 15244

Source:
Liu et al., 2015

Results from Canada on net effect

Implications for water footprint (WF) calculations:

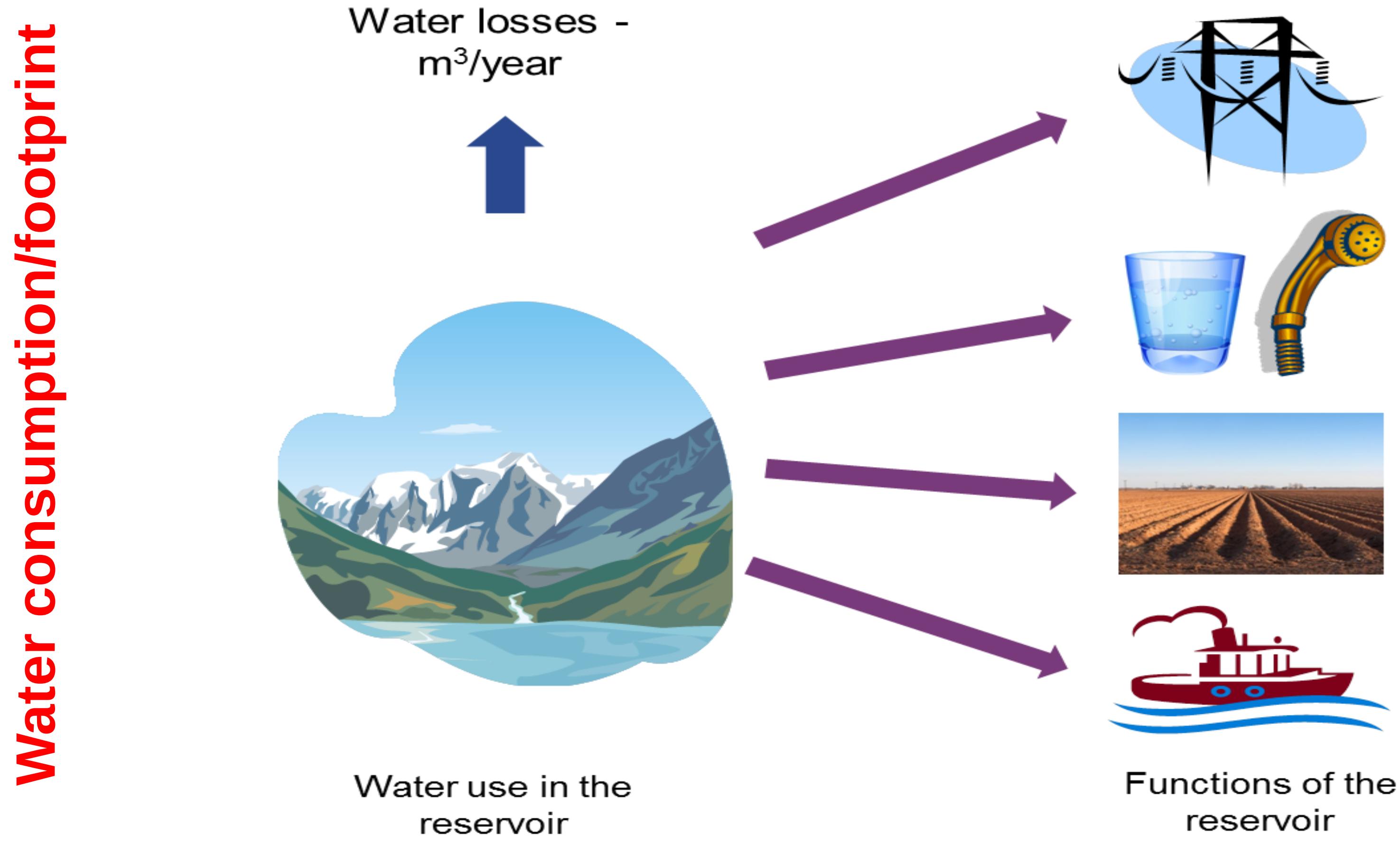
- Large uncertainties in evaporation leads to large uncertainty in WF
- Important to be able to diversify between land use/cover types, but difficult hydrological
- Assessment of net evaporation difficult with good precision
- The difference is smaller than the uncertainty?
- If limited difference in evapotranspiration between area types, net WF will always be (close to) zero.



As the reservoir is periodically a drawdown reservoir, they argue that the net change is negative (reduced evaporation)

Source: Tremblay et al., 2014

Allocation recommendations for multipurpose reservoirs



Lack of allocation methodology

IPCC SRREN (2011, Chapter 5, page 44) states that '*allocation schemes for determining water consumption from various reservoir uses in the case of multipurpose reservoirs can significantly influence reported water consumption values'.*

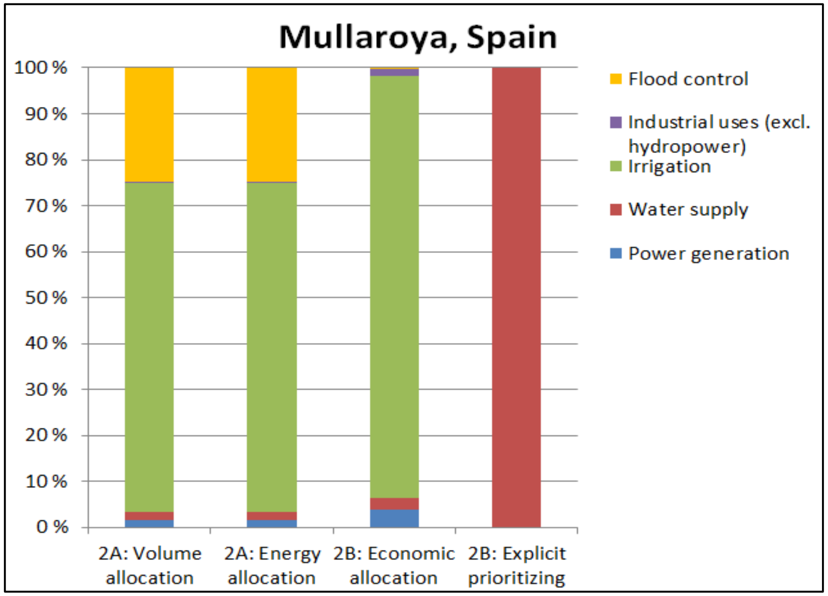
Problem confirmed in scientific literature (e.g. Mekonnen and Hoekstra, 2012; Pfister, 2011, Demeke et al., 2013; Bakken et al., 2013, Liu et al. 2015).

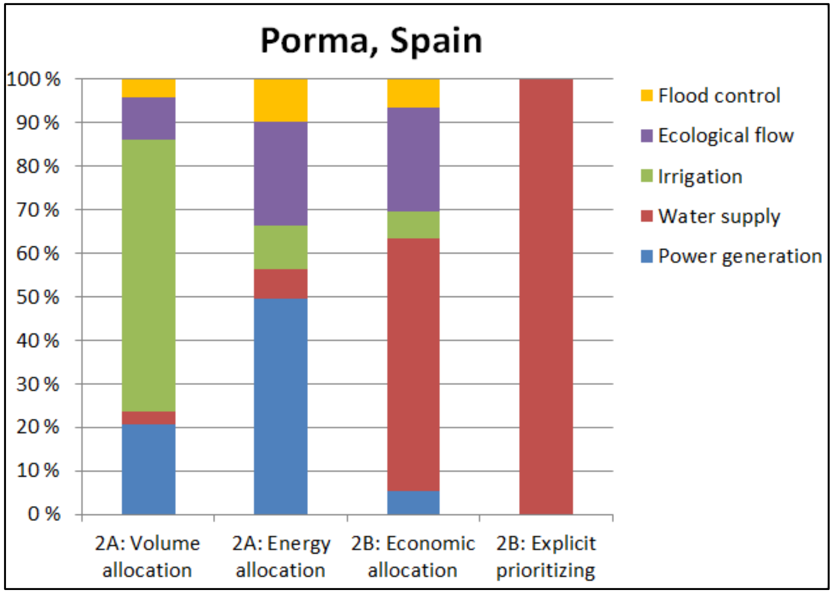
ISO Standard of Water Footprint (ISO 14046) suffers from clear guidelines on allocation.

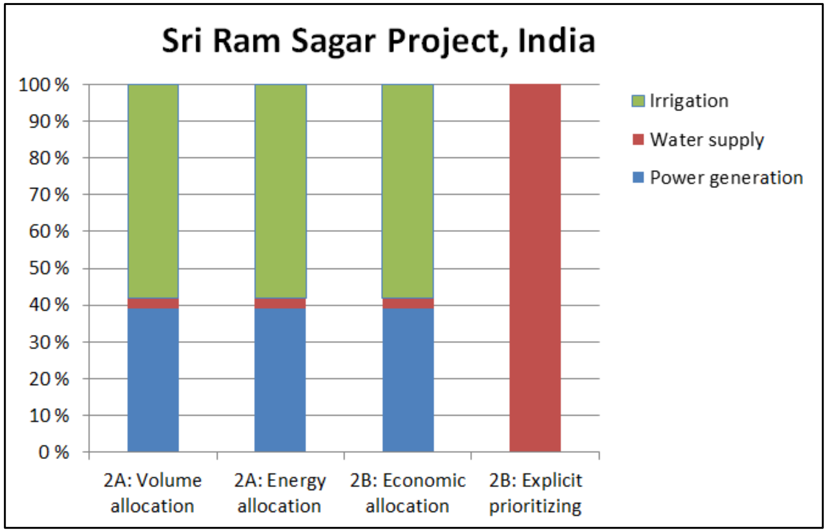
The work will also be useful for other environmental indices/parameters (e.g. GHG)

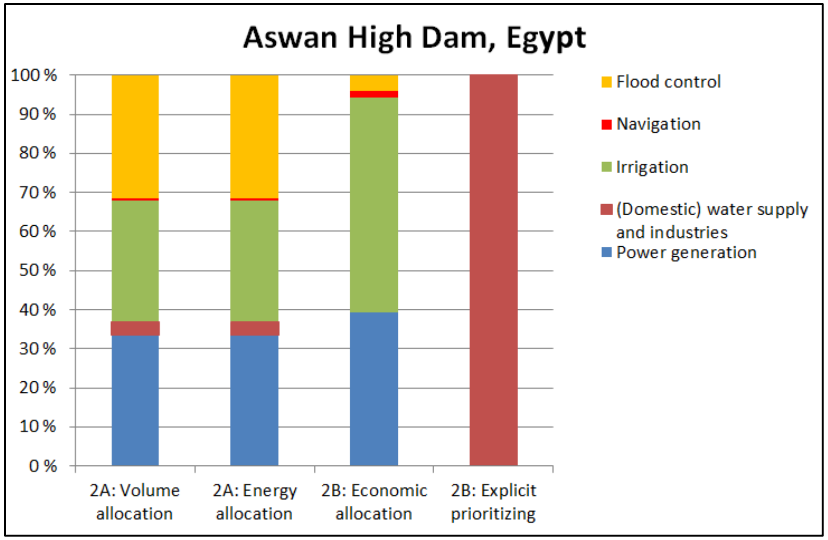
4 case studies

Allocation results









Recommendations

- We consider volume allocation to be the most robust approach in multipurpose reservoirs.
- We recommend that data should preferably be gathered from one source for all functions, to ensure a consistent calculation approach.
- The system boundaries should follow boundaries defined by the hydraulic system, but case-by-case adjustments will be needed to the site-specific character of the projects.

Full LCA of two hydropower projects

Rationale of study

Full LCA:

Construction of plant + Operation of plant + Decommission of plant

- It is assumed that the water footprint of hydropower is dominated by the operative phase (Inhaber, 2004; Fthenakis & Kim, 2010; Pfister et al., 2011; Mekonnen & Hoekstra, 2012). This is, however, not properly documented.

- How is the ratio between the water footprint in the operational phase versus the construction phase in an area with limited evaporation, a small reservoir, etc?

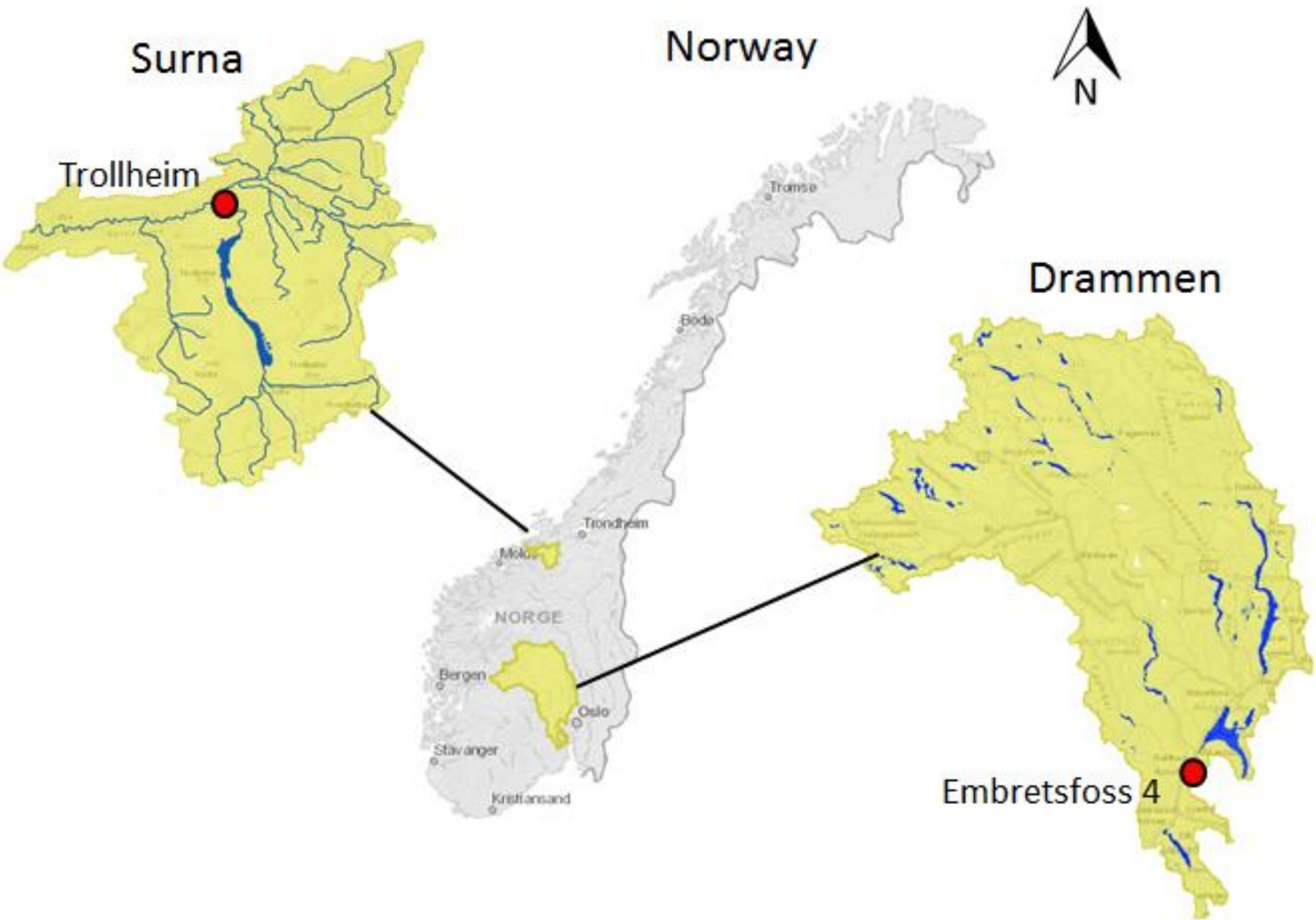
Case studies Norway

Trollheim HPP and Foldsjøen

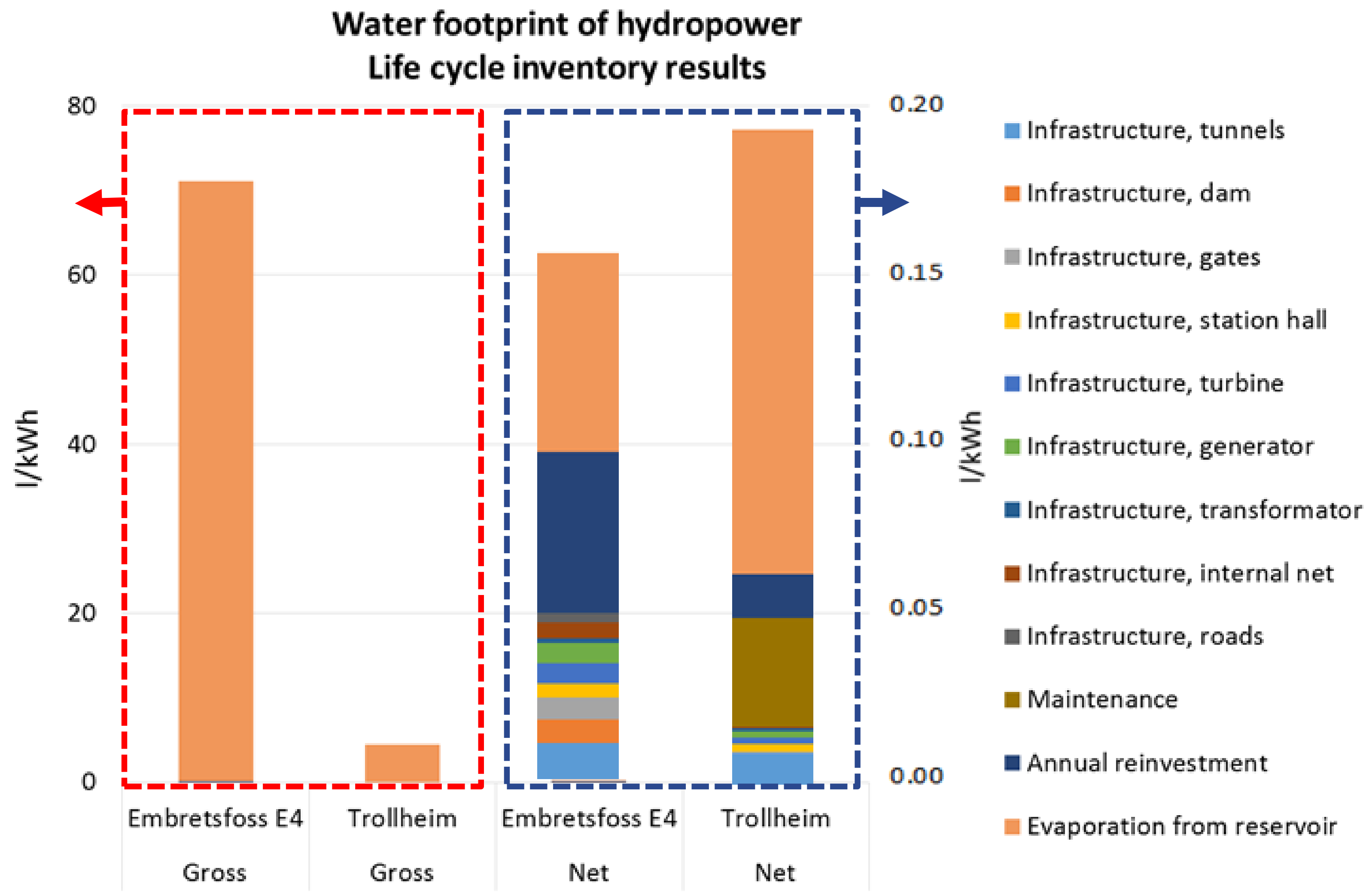
Embretsfoss 4 (ROR)

Known		Unknown		Known
↑		↑		↑
Construction of plant	+	Operation of plant	+	Decommission of plant

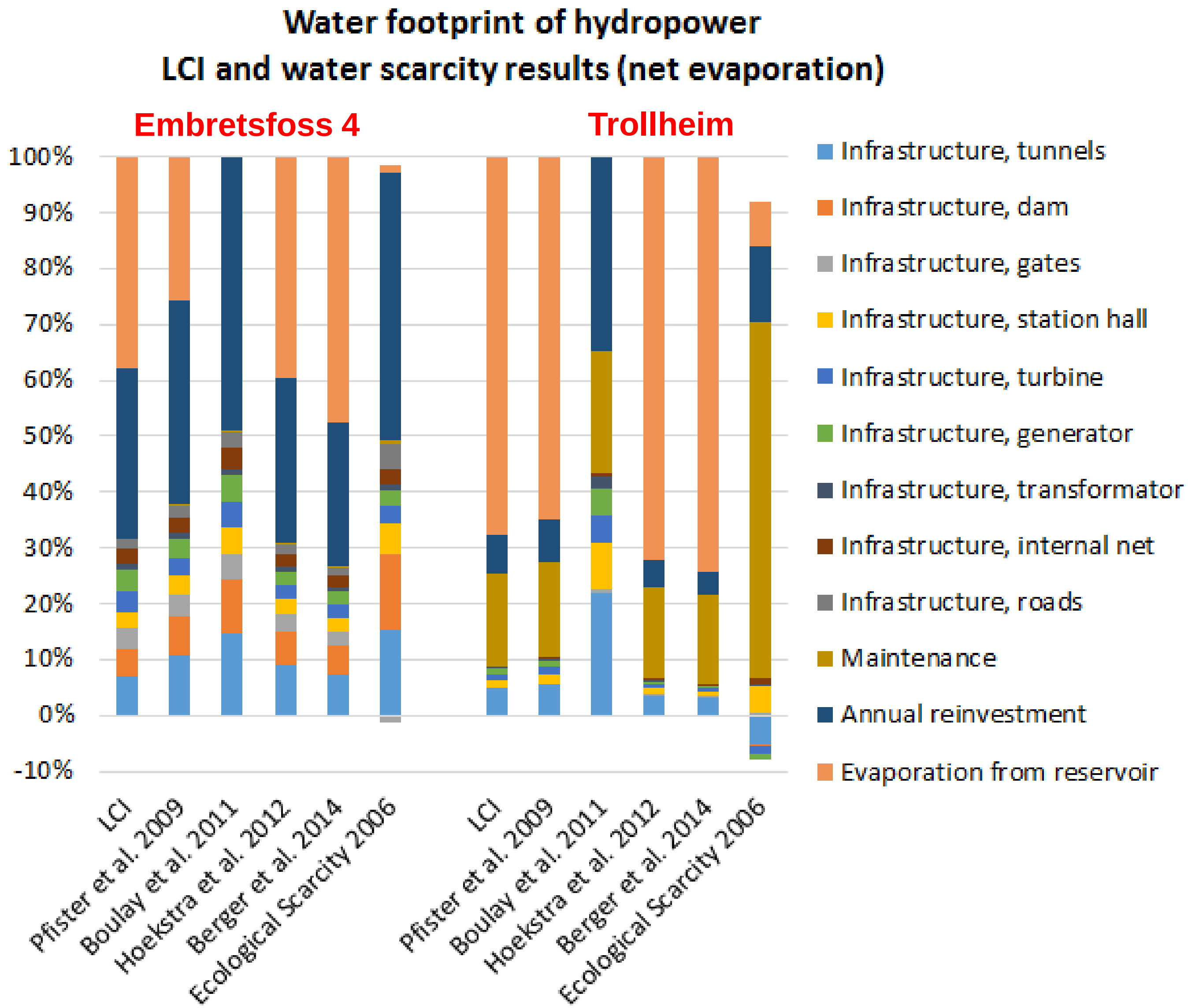
The two case studies



First results – non-categorized results



First results – categorized results/ratio



ICOLD-database

Contain information on a large number of dams > 15 meters

Holds information such as installed capacity, energy production, dam characteristics, country of location and purpose

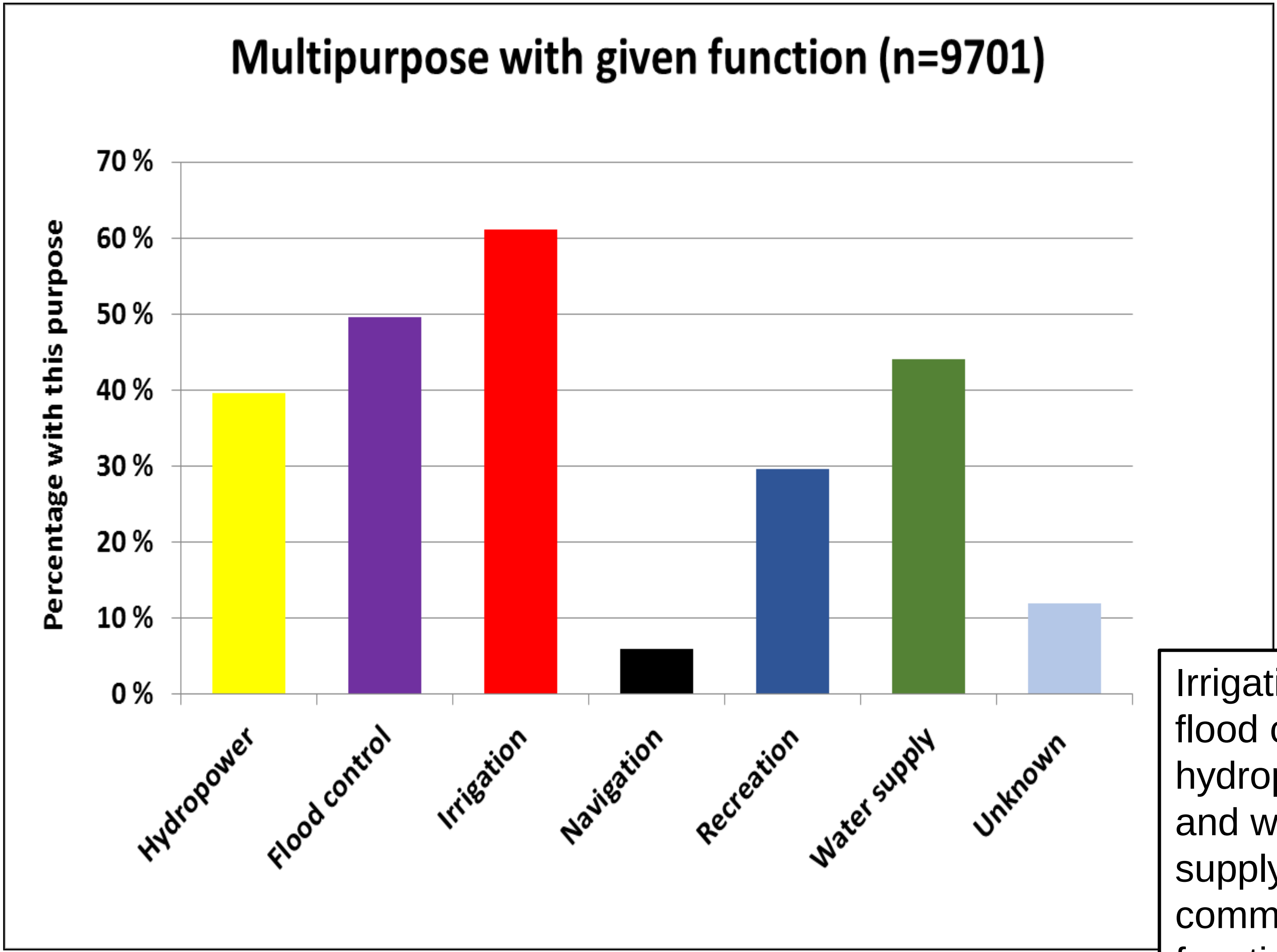
- single versus multi
- main purpose
- secondary purpose

Non-complete in terms of properties

Other sources estimate the total number of dams > 15 meters to be around 45 000 world-wide (ICOLD-web: ~ 50 000)

ICOLD:
World Register of Dams

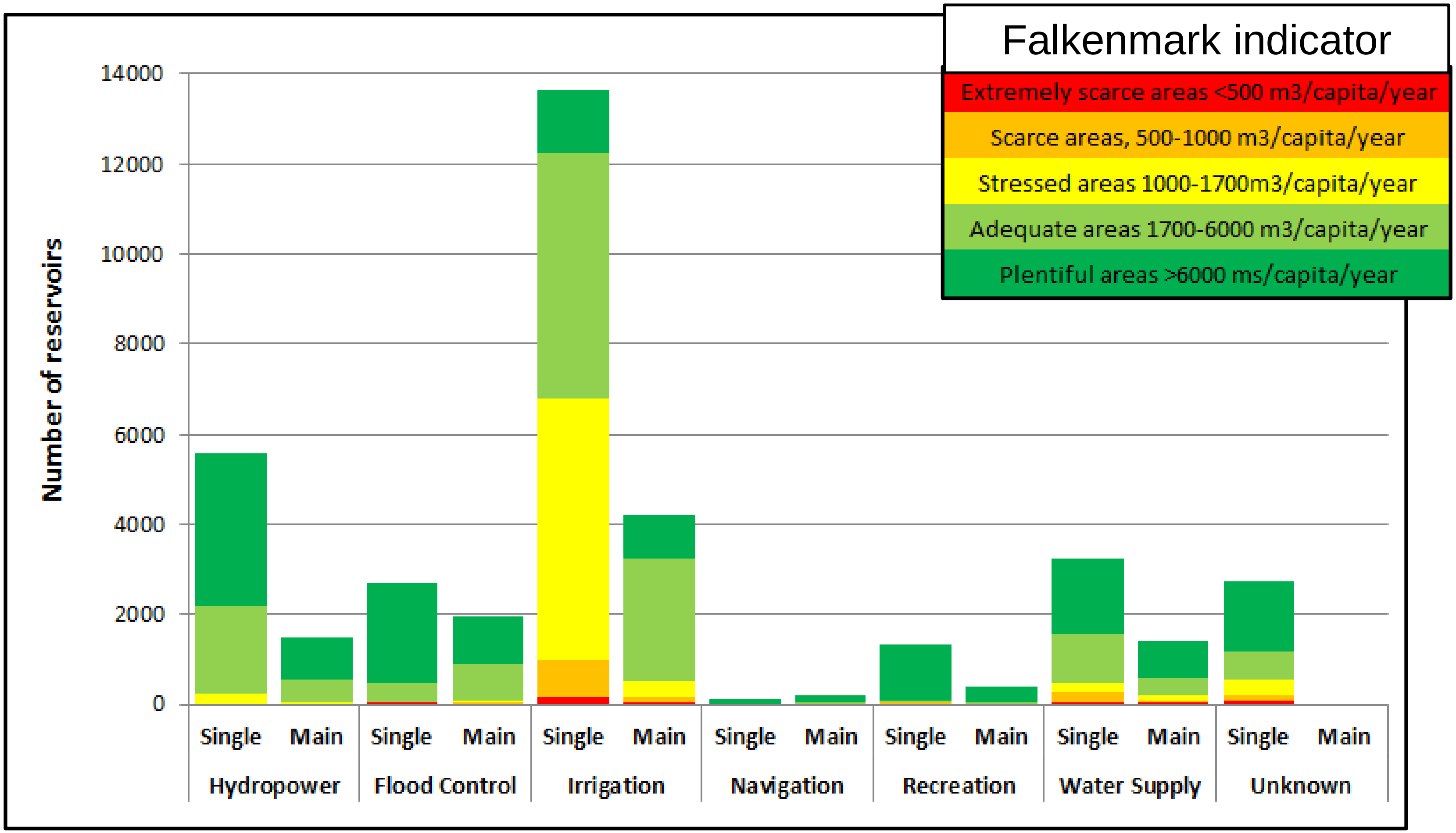
n=39188 by June, 2014
n=39064 for our study



Irrigation, flood control, hydropower and water supply are all common functions

Source: ICOLD database

Reservoir purpose (Single and Main) and water scarcity



Source: Bakken et al., 2015

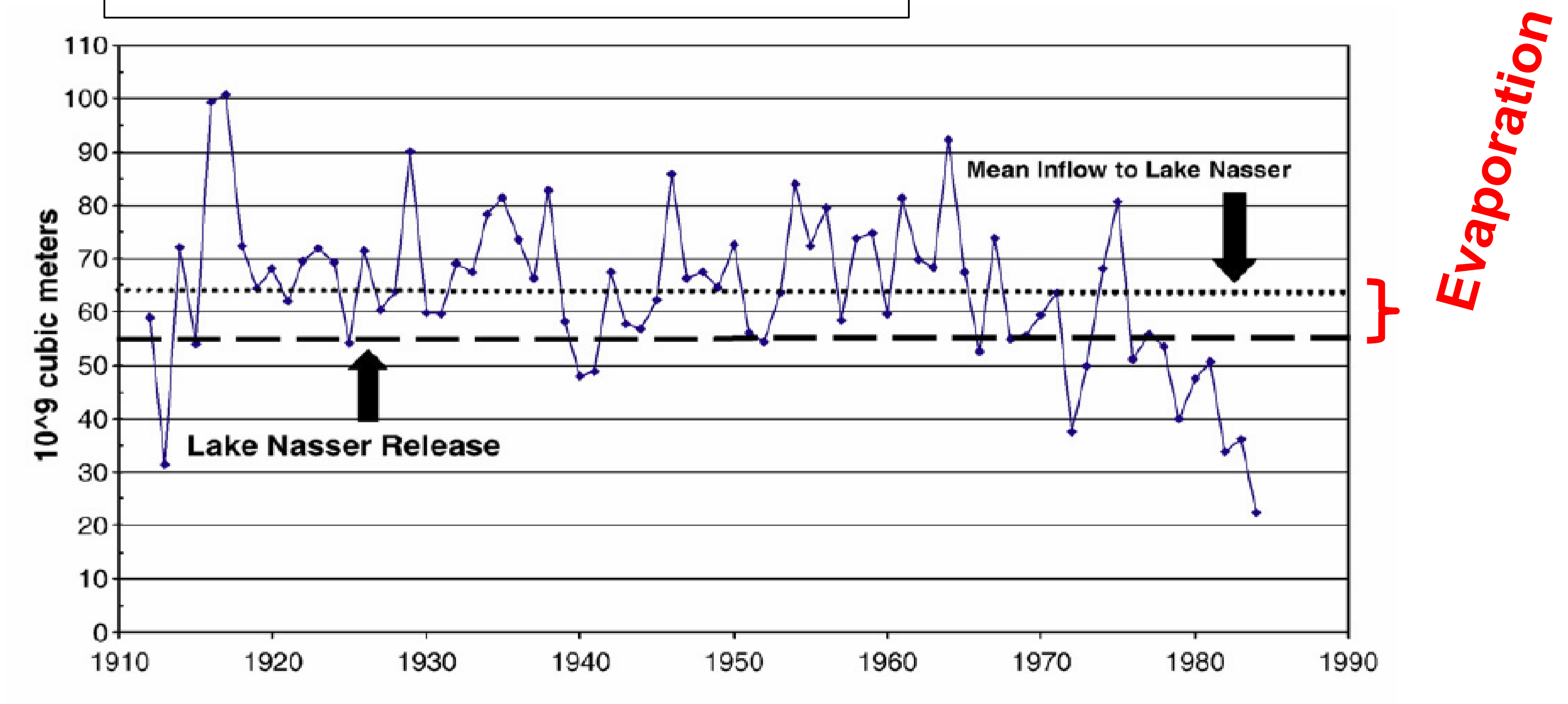
Reservoir purpose (Single and Main) and water scarcity

	Hydro-power		Flood Control		Irrigation		Navigation		Recreation		Water Supply		Unknown	
Scarcity level	S	M	S	M	S	M	S	M	S	M	S	M	S	M
Extremely scarce areas <500 m3/capita/year	3	2	35	14	53	45	0	0	0	0	13	1	82	0
Scarce areas, 500-1000 m3/capita/year	24	5	4	49	528	429	0	0	5	12	29	68	82	0
Stressed areas 1000-1700 m3/capita/year	703	162	44	41	6824	451	0	2	29	0	609	268	488	10
Adequate areas > 1700 m3/capita/year	4842	1306	2624	1835	6250	3275	100	184	1300	368	2597	1062	2095	112

Source: Bakken et al., 2015

Inflow & outflow
Lake Nasser (HAD) (Egypt)

Trade-off: Increased availability versus reduced annual volumes

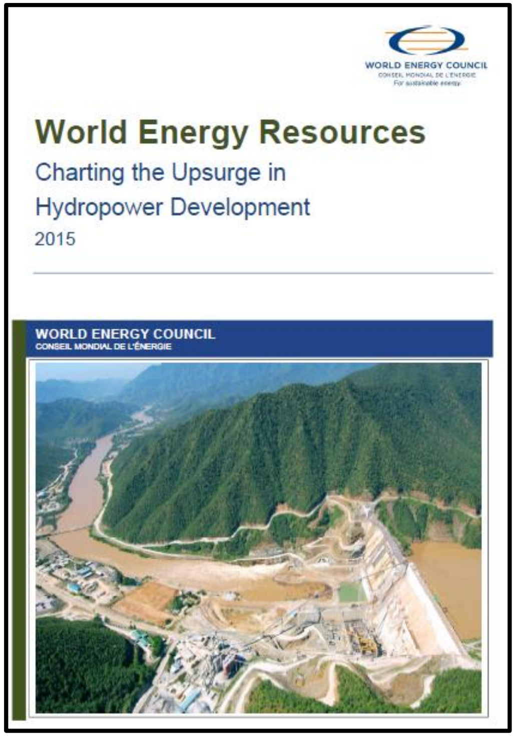


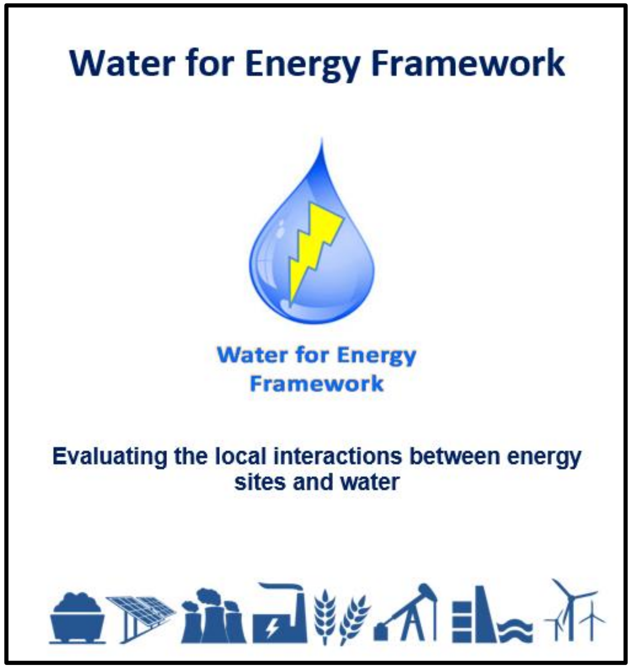
Strzepek et al., 2008

Summed up

- More studies are now published
- The data on hydropower is still very inconsistent, the old methodology frequently used
- Methodological problems investigated, solutions proposed, but not fully adopted by other scientists or the business
- Still an emerging topic in the industry/sector
- ISO standard on Water footprint (ISO 14046) now in place (?)
- Should a larger initiative be made among leading scientists, similar to on GHG?

External activity





+ meetings, seminars, conferences