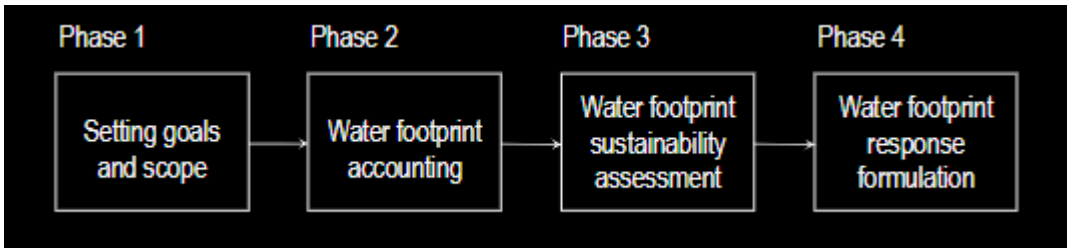
Lecture 1



Four thoughts WFA

1. Fresh water is a global source
2. Fresh water renewal raters are limited
3. Understanding natural resources and impacts → think in terms of supply chain and LCA
4. Green, blue and grey water

Common to all environmental footprints is that they quantify the human appropriation of natural capital as a source or a sink

Common pool = subtractable and non-excludable

Five drivers freshwater is overexploited → common pool, unpriced, externalization of downstream impacts, temporal misalignment, governance failure

Lecture 2 – WFA

WF = CropWaterUse/Yield

WaterProductivity = Yield/CropWaterUse

CropWaterUse = 10 * sum of Evapotranspiration (10 * is because from mm → m3 per ha)

The crop water footprint (ET) can be measured with a lysimeter and Bowen ratio measurement system for example or measured with remote sensing, but it is difficult to distinguish individual crops, separate green/blue water contributions and you cannot explore different scenarios. So, we use crop modelling.

Crop modelling allows the assessment of:

- Large scale patterns in space
- Developments over time
- Climate change scenarios
- Management scenarios
- But is computationally intensive and calibration is often not feasible

Crop water requirement approach:

- CWR = ETc = Eto * Kc
    - Kc empirically determined for many crops
- Eta = actual ET ≤ ETc
- Peff = effective precipitation
- ETgreen = the minimum of Peff or ETc
- Irr req = 0 or the ETc – Peff (choose biggest value)
- ETblue = alfa * Irr req → alfa is application efficiency of irrigation water
- Actual crop yield is calculated as faction of maximum yield possible

$$\left(1-\frac{Y_a}{Y_m}\right)=K_y\left(1-\frac{\sum ET_a[t]}{\sum CWR[t]}\right)$$

Soil water balance approach:

- Estimate CWR = Eto * Kc
- Estimate ET from actual soil water availability estimated with daily soil water balance method → ETa = CWR * Ks
- No feedback between soil-crop → crop coefficient and rooting depth over season pre-described and not simulated, water stress does not affect crop and root growth (water stress does affect yield wit the same fraction as CWR approach)

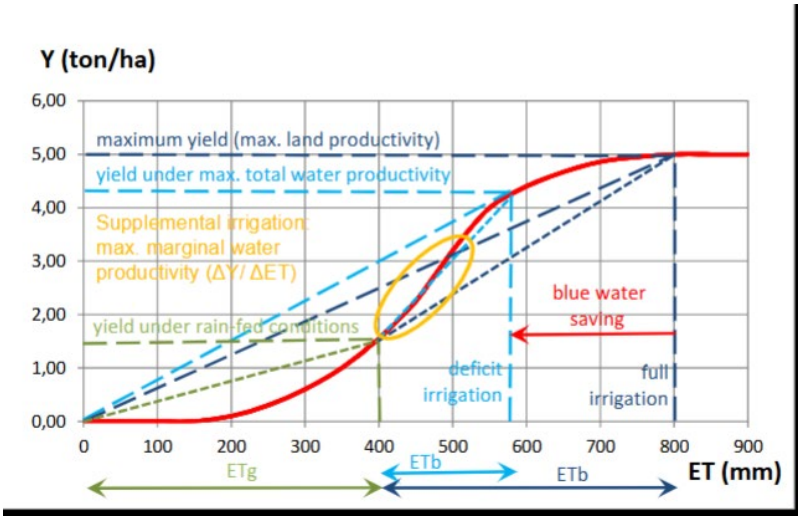
Crop model approach:

- Simulation of soil water balance and ET + crop/root development, biomass and Y
- Process based
- Feedback between soil-crop-atmosphere
- Time is in growing degree days
- Has separate for transpiration and soil evaporation and CC is affected by stresses and determined Kc
    - Tr = Ks * CC * Kcbx * Eto
- Aquacrop: intended for practitioners as a planning tool to assist management decisions in both irrigated and rainfed agriculture and is widely used in research. It is a water driven crop growth model, particularly suited to address conditions where water is the key limiting factor. It only has a few number of parameters which should be given to the model
    - 1. Water balance → 2. Crop development → 3. Transpiration → 4. Biomass → 5. Yield

Overview:

Approach	Calculation of ET	Crop development	Crop yield	Read more
Crop water requirement	Effective precipitation	Pre-described crop factor	Estimated based on ET vs CWR	App. I-II WFA Manual; 'crop water req. option'
Soil water balance	Daily water balance	Pre-described crop factor & root depth	Estimated based on ET vs CWR	App. I-II WFA Manual; 'irrigation schedule option'
Crop model	Daily water balance	Simulated	Simulated biomass x HI	Sect 4.2.2 Schyns et al. (2022) in *Food Systems Modelling*
		Feedback loops		

What can we do to reduce the WF of crops?

- Mulching
  - Reduced soil evaporation and increased Y because of enhanced soil structure, reduced erosion and weed growth
- Irrigation technique
  - Reduced soil evaporation
  - Increased Y because of increased plant transpiration
- Irrigation strategy
  - Full → meet CWR, maximize Y
  - Deficit → reduce irrigation water use at minimum loss of Y, minimize unit WF (maximize WP)
  - Supplemental → increase Y compared to rainfed with minimal water applied
- 

For only better yield: eliminate stress factors such as weeds, diseases, lack of nutrients and salinity

Lecture 3

Direct water use of person → 129 litre/person/day

Why should we care about the size of our WF of consumption

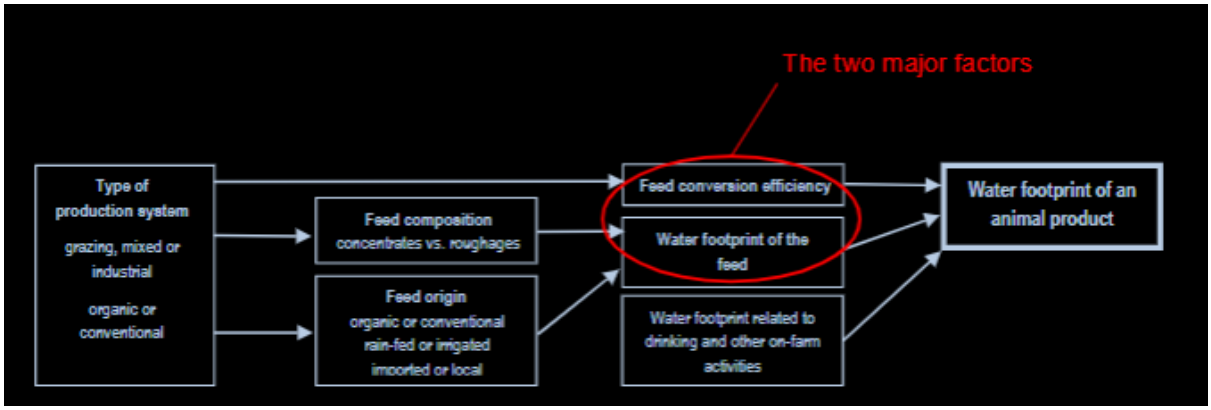
- Freshwater is limited, while the demand is growing
- The maximum sustainable WF per person is decreasing
- Sustainable levels of water use are already exceeded locally
    - And will be exceeding more aften under business as usual
- Water footprint of consumption is unequally distributed

We drink 6 bathtubs of drink every day.

Meet and especially beef has a high water footprint. It has a higher footprint than pork and poultry.

Beef can have a different sustainable impact because of different ways of cultivaitng

- Grazing systems → mostly green and local
- Mixed systems → green blue gray and local
- Industrial systems → green blue gray and partly imported



The feed conversion efficiency improves from grazing to industrial system, but at the cost of more high nutrient concentrate feed with a larger water footprint than roughages.

When cattle grazes in a dry land water footprint has a low opportunity cost. There are not a lot of other things that would have grown there.

Reduce water consumption:

- Produce feed in rain-fed agriculture and increase green water productivity
- From industrial towards grazing or mixed systems → reduce concentrate feed
- Grazing in areas unsuitable for crop growth

Reduce water pollution:

- Organic or precision farming → reduce use of fertilisers and pesticides
- No preventive antibiotics, no excessive manure

There is a need for product transparency, because beef can differ a lot

Food item	Water footprint			
	Litre per kg	Litre per kcal	Litre per gram protein	Litre per gram fat
Sugar crops	197	0.69	0.0	0.0
Vegetables	322	1.34	26	154
Starchy roots	387	0.47	31	226
Fruits	962	2.09	180	348
Cereals	1644	0.51	21	112
Oil crops	2364	0.81	16	11
Pulses	4055	1.19	19	180
Nuts	9063	3.63	139	47
Milk	1020	1.82	31	33
Eggs	3265	2.29	29	33
Chicken meat	4325	3.00	34	43
Butter	5553	0.72	-	6.4
Pig meat	5988	2.15	57	23
Sheep/goat meat	8763	4.25	63	54
Bovine meat	15415	10.19	112	153

	Meat diet			*Vegetarian diet*			*Vegan diet*		
	kcal/ day	*litres/ kcal*	*litres/ day*	*kcal/ day*	*litres/ kcal*	*litres/ day*	*kcal/ day*	*litres/ kcal*	*litres/ day*
Plant-based	2,450	0.7	1,715	2,950	0.7	2,065	3,400	0.7	2,380
Dairy and eggs	450	1.7	765	450	1.7	765	0	1.7	0
Meat and fish	500	4.0	2,000	0	4.0	0	0	4.0	0
Total	3,400	1.3	4,480	3,400	0.8	2,830	3,400	0.7	2,380

Source: Hoekstra (2020) The Water Footprint of Modern Consumer Society: Second Edition, Routledge, London, UK.

-37%

-47%

The water section is becoming more energy intensive:

- Desalination
- Pumping deeper groundwater
- Large-scale inter basin water transfers

The energy sector is becoming more water intensive:

- Shale oil and gas fracking: Hydraulic fracturing requires millions of gallons of water per well mixed with sand and chemicals, pumped deep underground at high pressure to crack open rock formations and release trapped hydrocarbons
- Tar sand and oil/kerogen shales: **:** Extracting oil from tar sands (via surface mining or steam-assisted gravity drainage) and heating kerogen shales requires

immense volumes of steam and water to separate, wash, and process heavy bitumen, far exceeding traditional crude extraction.

- Biomass: Growing energy crops (like corn for ethanol or sugarcane) requires extensive agricultural irrigation, making bioenergy one of the most water-intensive energy options per unit of energy produced

Source	Energy products after combustion	Liquid or solid energy products
Starch crops (barley, cassava, maize, paddy rice, potato, sorghum, rye, wheat)	Heat, electricity	Bio-ethanol
Sugar crops (sugar beet, sugarcane)	Heat, electricity	Bio-ethanol
Oil crops (soybean, rapeseed, jatropha)	Heat, electricity	Bio-diesel
Trees (poplar)	Heat, electricity	Charcoal
Organic waste	Heat, electricity	Bio-ethanol

- Hydropower: the global blue WF of reservoirs worldwide is 250* 10^9m3/year, this is 25% of blue WF of agriculture industry and households. 41% of this WF is ultimately attributed to hydropower. Uses water because of evaporation

New scenarios want more biofuel → this uses a lot of water

Lecture 4

The grey water footprint = volume of freshwater required to assimilate the load of pollutant in order to maintain the quality of the ambient water above the agreed water quality standards

Why the pollution load concerns more than one form of pollution

1. Estimate the grey WF for the different pollutants
2. The grey water is determined by the pollutant that is most critical e.g. the one that is associated with the largest pollutant specific grey WF

Point source pollution: a stationary location or fixed facility from which pollutants are discharged, any single identifiable source or pollution

$$Grey\ WF = \frac{L}{c_{max} - c_{nat}} = \frac{Effl \times c_{effl} - Abstr \times c_{act}}{c_{max} - c_{nat}}$$

If Effl = Abstr then: $Grey\ WF = \frac{c_{effl} - c_{act}}{c_{max} - c_{nat}} \times Effl$

If ceffl = cact → WF = 0, concentration of receiving water body will remain unchanged
If ceff > cact → WF > 0, even when effluent concentration is lower than maximum allowable concentration in receiving water body: reason → *some of the capacity to*

assimilate pollutants have been consumed

If ceffl < cact → WF = 0

Critical load =(cmax – cnat) * freshwater availability → means that assimilation capacity is fully consumed

WFgrey < fresh water availability → assimilation capacity not fully used

WF grey = fresh water availability → full assimilation capacity of the river is used → load = critical load

WFgrey > R → pollution exceeding the assimilation capacity of environment

$$Grey\ WF_{proc} = \frac{Effl \times \Delta T_{effl}}{\Delta T_{max}} = \frac{Effl \times (T_{effl} - T_{act})}{T_{max} - T_{nat}}$$

Diffuse pollution: Pollution from widespread activities with not one discrete source

$$\text{Grey WF} = \frac{L}{c_{max} - c_{nat}} = \frac{\alpha * Appl}{c_{max} - c_{nat}}$$

Applic. rate (AR) = 1 kg/ha
Leaching-runoff fraction (α) = 5%
A = 30 million ha

► $L = \alpha \times Appl$ = 1.5 million kg/yr

c_{max} = 3 µg/l (EPA, 2005)
c_{nat} = 0 µg/l

► Total grey WF of activity = $\frac{L}{c_{max} - c_{nat}}$

Y = 9 ton/ha → Prod = 270 million t/yr

= 500 x 10^9 m^3/yr

► Grey WF per unit of product = $\frac{\frac{L}{c_{max} - c_{nat}}}{Prod}$

= 1852 m^3/t



Plane spraying pesticide on maize (*Zea mays*), California, USA

The three tier approach of grey WF

1. Simply uses a leaching-runoff fraction to translate data on the amount of a chemical substance applied to the soil
    a. Fraction is derived from existing literature of estimated based on the experience of expert panel
2. Applies standardized and simplified model approaches
3. Uses sophisticated modelling techniques and/or intensive measurement approaches

When information of the influencing factors is available, a simple table and equation can be used to derive a more specific estimate of the leaching run off fraction

1. Physical chemical properties of the chemical substance applied
2. Management practices
3. Environmental practices

The more specific value will fall between the minimum and maximum value depending on the influencing factors. There is a table to derive the leaching run off potential

How to integrate over time and different pollutants

1. Estimate the grey WF of different pollutants
2. The grey WF is determined by the pollutant that is most critical E.G. the one that is associated with the largest pollutant specific grey WF
3. Do not sum the grey WF related to different pollutants togheter

But there is some evidence found that the combination of pollutants can be deadly, so might not be the best method

Water pollution level = grey WF / runoff, when WPL > 1 water quality standards are violated

Risks of pharmaceuticals in water

- Ecotoxicity
- Resistant bacteria
- Pharmaceuticals reach drinking water and cause risks for humans, but missing information on long-term exposure at low doses
- Metabolites and transformation products

The grey water footprint on pharmaceuticals is new research field → there are no guidelines. For point sources the load estimation was quite straight forward, but for diffuse sources from livestock agriculture, an approached was developed and the first were presented using a precautionary principle – as a next step need to develop a more sophisticated approach, which should be further developed in future.

Critical aspects of water pollution levels:

- Temporal variability
- Human interaction into hydrological system
- Combination of both

Challenges for grey water footprint

- Data scarcity

- Diversity of pollutant, sources and complex emissions/fate processes make GWF estimation a challenging task → using and combining other data sources (LCA) and emission models

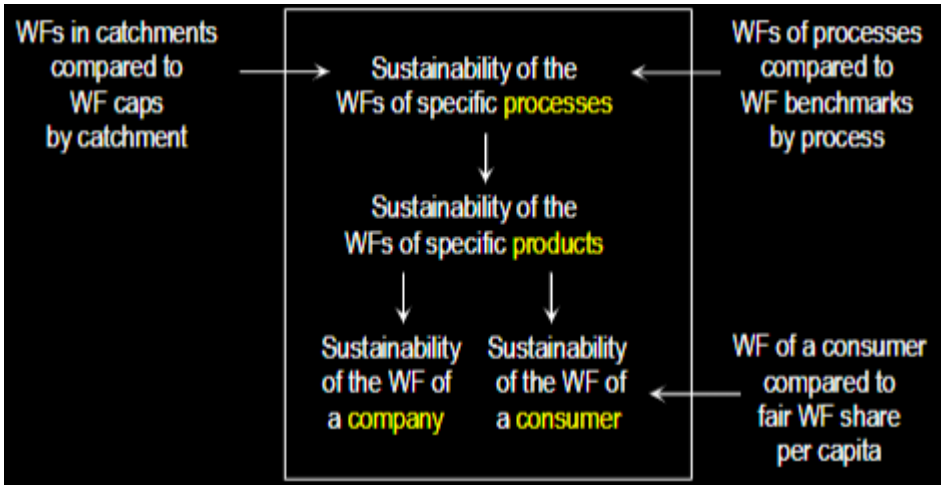
Lecture 5

It is impossible to establish the sustainability of a single item

- Depends on context and cumulative impacts/aggregated effect

The environmental footprint assessment is system centric (assess sustainability at macro-level) and difficult to allocate overall unsustainability to specific products

Life cycle assessment is product centric (comparative approach of size of potential impacts) and difficult to draw conclusion at system level



Assessing the sustainability of a product water footprint

- Consider each component of the WF of a product or company separately
- Evaluate the sustainability per component based on two critera
    - Is the wf component located in a hotspot → compare wf in a catchment to wf cap in the catchment
    - Can the wf be avoided or reduced at reasonable societal costs → compare wf of a process to wf benchmark for the process

Hotspots are catchments in which: XXX water footprint > XXX water availability

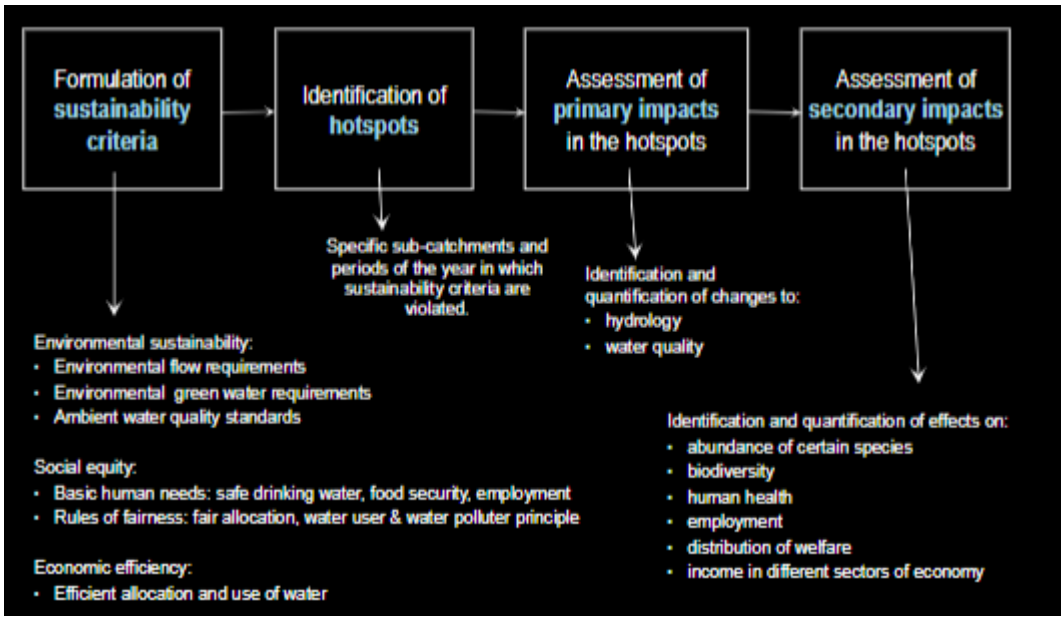
Green water availability = total evapotranspiration – ET from land reserved for nature – ET from non-nature areas that cannot be made productive

Green water scarcity = green water footprint/ availability

Blue water availability = natural run off – environmental flow requirement (often 80% of natural runoff)

Blue water scarcity = blue water footprint / availability

Two methods for water footprint benchmarks → ranking and best available technology



Different flows

- Environmental flow = the freshwater regime provided within a river, wetland or coastal zone to maintain ecosystems and their benefits where there are competing water uses and where flows are regulated
    - Allocated to a river is primarily a matter of social choice, with science providing support in terms of what the river ecosystem will be like under various flow regimes
- Environmental flow requirement = the freshwater regime required to meet a defined objective with respect to desired ecosystem characteristics
    - Are to be weighted with other water needs like those of hydropower generation, irrigation, drinking water, flood mitigation and recreation
- Natural flow = the freshwater regime if there were no human influence

Alterations of natural flows → direct diversion of water flows (net water abstractions), transformation of the stream network (dams and reservoirs, river canalisation), chaning drainage basin characteristics (land use), activities altering regional or global climate

How to asses environmental flow requirements

- Hydrological indices → minimum flow standards (percentage of mean annual flow, variable percentages of the monthly mean flow percentile from a flow duration curve)

- **Environmental flow requirement = LFR + HFR**

  Low flow requirement (LFR)
  LFR = Q90 (monthly flow that is exceeded 90% of the time)
  Q90 mostly falls between 0 and 50% of mean annual runoff (MAR)

  High flow requirement (HFR)

Highly variable flow regimes	Q90 < 10% MAR	HFR = 20% MAR
	10% MAR < Q90 < 20% MAR	HFR = 15% MAR
	20% MAR < Q90 < 30% MAR	HFR = 7% MAR
Very stable flow regimes	30% MAR < Q90	HFR = 0

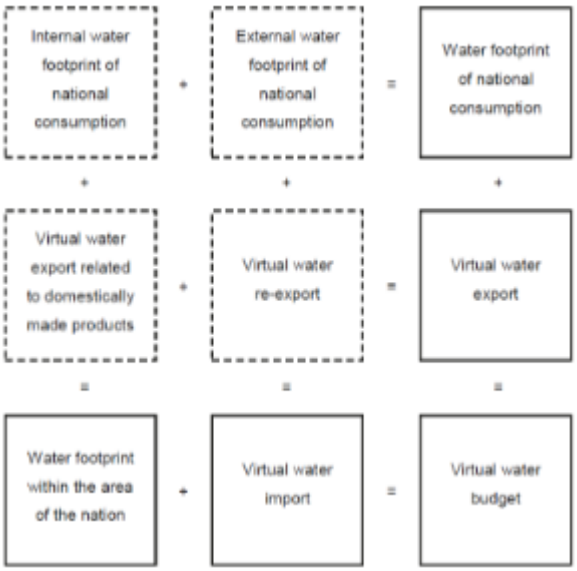
- Flow regime characteristics
  - Range of variability method
    - Identification of the components of natural flow regime,
    - Set of 32 hydrological indices describing the natural flow regime in terms of flow magnitudes, timing frequency and duration
    - Each index is calculated on an annual basis for each year in the hydrological record
    - An acceptable range of variation of the indices is set the standard deviation from the mean or between 25-75 percentiles
- Hydraulic rating method
  - Targets with respect to wetted perimeter

Habitat modelling → modelling the relation between hydrology and the physical characteristics of the habitat of target species (USA's physical habitat simulation)

Functional analysis → analysis of relation hydrology to river system ecology (south africa: building block methodology → riverine species are supposed to rely on basic elements of the flow regime) and Australia's expert panel assessment method, scientific panel approach and benchmarking approach)

Socio-ecological methods → hydrological + habitat + eco system + socio-cultural/ecoomic factors

Lecture 6



National water footprint accounts → high spatial resolution, ten year period, specified by consumption category, both internal and external, explicit distinction in grey, blue, green

Major determinants of the water footprint of national consumption

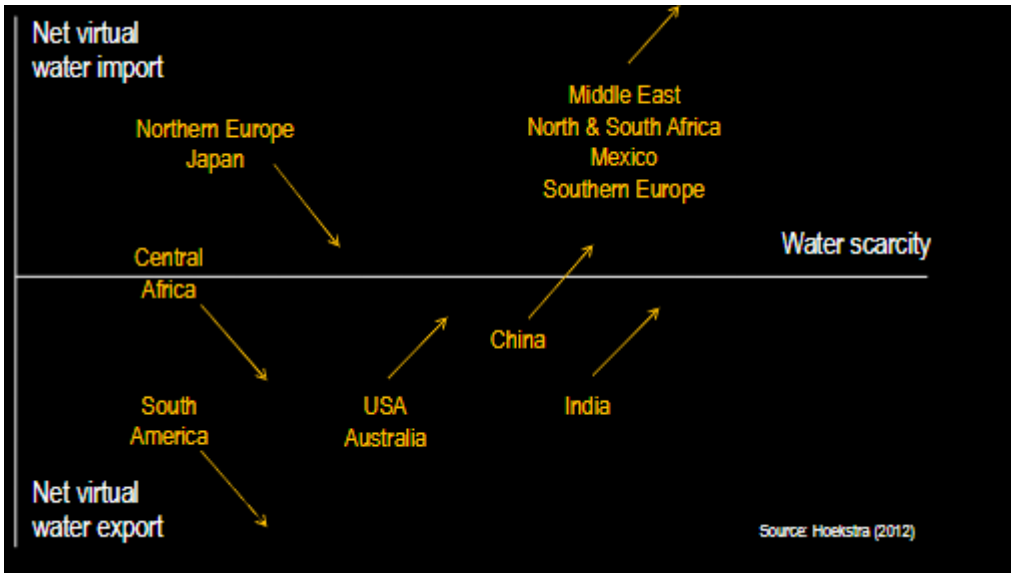
1. Consumption characteristics → consumption pattern, consumption volume
2. Production circumstances → climate (ET), agricultural practice (WP)

Net exporters: north and south america, southern asia, and australia

Net importers: north africa, middle east, mexico, europe, japan and south korea

25% of the wf on earth is for making export products

How patterns will change due to climate change:



National wate saving → a natian can save water by importing water-intensive commodity instead of producing it domestically

Global water saving → international trade can save water globally if a water-intensive commodity is traded from an area with high to an area with low water productivity

When externalizing water footprint countries can achieve huge national water savings because of trade for example when there is not enough water available in that country.

Drawbacks of importing water-intensive agricultural products:

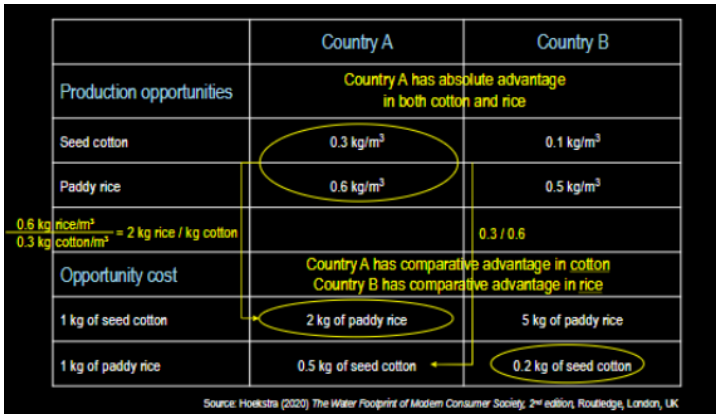
- Affordability of imports
- Reduced food self-sufficiency
- Domestic socio-economic effects
- Externalized pressures of fresh water

Externalized pressure on freshwater of NL → 43% of blue WF of Dutch consumption is unsustainable and 61% of the unsustainable parts is located in 6 countries (Pakistan, USA, Spain, India, Egypt, Iran)

Recall from Globalization of Water Roleplay:

- Countries can benefit from trade with one another, when they produce and export the goods that they have a comparative advantage in.
- Countries differ in production circumstances, so that each country has different opportunities to produce a certain good.
- Countries with relative water abundance or relatively high water productivity, or a combination of both, will have a comparative advantage in producing and exporting commodities that are relatively water-intensive,
- because they have the lowest opportunity costs for producing those commodities

We can calculate comparative advantage → first calculate opportunity cost



Reality is more complex as there are many countries and other products and production factors. To which degree water explains trade depends on how scarce water is compared to other production factors.

Projection to 2050: population growth → BWA per capita reduces → import of stable crop increases by a factor of 1.4-1.8 to meet the stable food needs of the 42 most water scarce countries

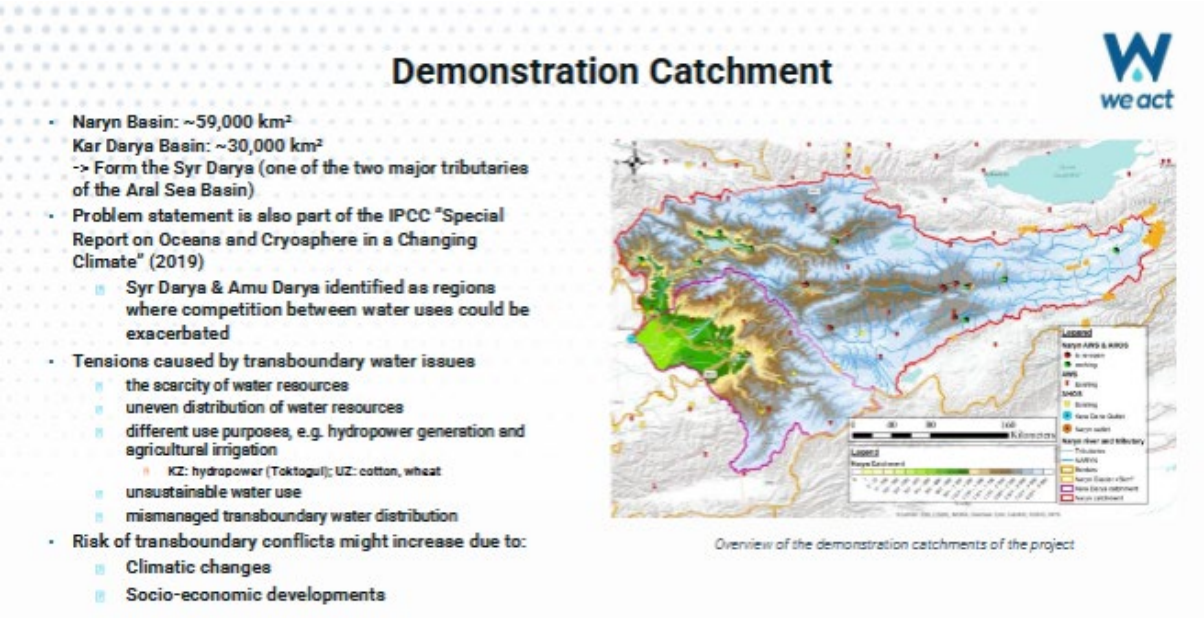
The water scarcity – export parados: Water intensive commodities that are produced in water-poor regions and exported to relative water rich regions (virtual water transfer), physical water transfers occur in the opposite direction to enable the former. Marocco and China made water pipes to pump water to the water poor regions from the water rich regions.

Why grow in water poor areas?

- Interplay of historical, political and economic reasons
- Water scarcity → incentive to increase water use efficiency → comparative advantage in water intensive commodities → virtual water export

Lecture 7:

Case study Syr Darya basin: Rivers are Syr Darya and Amu Darya



Problems → scarcity of water resources, uneven distribution of water resources, different use purposes (hydropower Kazakhstan /agriculture Uzbekistan), unsustainable water use, mismanaged transboundary water distribution → might increase due to climate change and socio-economic developments.

Balanced water management includes: environmental sustainability, resource use efficiency, social equity, resource security

Read documents on canvas for examples for indicators and interventions and if they are synergies or trade offs

Tradeoff → in an intervention for one objective undermines another (e.g. rip irrigation improves efficiency but reduced equity due to cost)

Synergy → if an intervention for one objective benefits another (drip irrigation improves efficiency and sustainability)

Lecture 8:

Phase 4 → water footprint response formulation

Targets for sustainable water use:

Dimension/issue	Potential target	Potential means
Environmental sustainability	Reduce WF within catchments to maximum sustainable levels	WF caps by river basin
Economic efficiency	Reduce WF of products to reasonable levels	WF benchmarks by product (based on best available technology or in the top 20%)
Social equity	Reduce WF of communities to fair levels	Fair WF shares by nation
Resource security	Reduce unsustainable external WFs per country or region	Max. degree of import dependency per country

Sustainable development goals:

- Target 6.3: By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally
- Target 6.4: By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity.

Strategies: most import hotspot with large reduction potential, after that or a hotspot with little reduction potential or a non-hotspot with large reduction potential and lastly a non hotspot with little reduction potential.

Priorites:

1. Prevent → reduce by avoid: do not undertake water-using and polluting activities together
2. Control → reduce by improved production: replace one technique by another technique that results in a lower or even zero water footprint
3. Offset → compensate the residual water footprint by making reasonable investment in establishing or supporting projects that aim at sustainable, equitable and efficient use of water in catchment where the residual water footprint is located

When focus on domestic water saving → reduce water use in nation, increase virtual water import, reduce virtual water export

When focus on sustainable consumption → reduce the water footprint of consumption

Policy instruments

- Institutional arrangements
- Regulatory instruments
- Economic instruments
- International agreements

Example of regulatory instruments:

- water footprint caps per catchments
- water footprint benchmarks per process and product → wheat benchmark set by the best 25% of global production, would result in a global water saving of 39%
    - Take the WF of the best 20th percentile of production as a reference
    - Best available technology (BAT) / best practices
        - Drip irrigation (technology) for blue WF in crop growing
        - Precision irrigation (practice) for Blue WF in crop growing
        - Organic farming for grey WF in crop growing
        - Make rainwater more productive: lower green water footprint
        - Full water recycling for blue WF in industry
        - Closed cooling for blue WF in industry
        - Full waste water treatment for grey WF from domestic waste water
    - Zero blue and grey wf in industrial processes4
- Product labelling and certification
- Water footprint permit system
- Minimum water rights

- Enforcement on illegal water abstractions
- Water neutral spatial development (water en bodem sturend)

Economic instruments:

- Water tariffs and pricing
    - Water price should include: water supply infrastructure, operation-maintenance costs (water prices are now only based on OM costs because water is seen as common pool resource), economic externalities, environmental externalities, water scarcity rent
- Water pollution charges/taxing
- Taxing water-intensive commodities
- Water markets and trading
- Subsidies and rebates

International agreements:

- International WF reduction agreement on specifying targets per country
- Minimum water rights
- International water pricing protocol
- International trade rules
    - No discrimination principle in WTO → a country should not discriminate between its trading partners nor between its own and foreign products
    - Product transparency vs non-discrimination in trade
    - Non-discrimination principle can be overruled only by trade restrictions included in international environmental agreements
    - Absence of international agreements on sustainable water use
- International nutrient housekeeping agreement
- Internation WF standards
    - The water footprint assessment manual

Shared responsibility

- Direct responsibility
    - Governments
    - Direct water users: farmers, industries, households, water supply utilities
- Supply chain responsibility
    - Consumers
    - Companies
    - Investors
    - International cooperation
- Media
- Academia
-

Who	What
Government - Ministries - Provinces - Municipalities - Water boards - River basin committees	- Taxing water-intensive commodities (e.g. meat, dairy, cotton) - Regulations or incentives (e.g. taxes, subsidies) for companies to produce more sustainable and resource efficient - Awareness raising campaigns - Taxing water-intensive goods from water-scarce places - Regulation on (obligatory) product labelling - Coherent/harmonised policies across policy domains (agriculture, energy, consumption, trade, spatial planning and demography) - Water pricing - Water footprint caps per water body (aquifer, river basin) - Development of WF benchmarks for different products/sectors. - Water allocation based on WF permits (accounting for WF caps per water body and WF benchmarks per water user) - Water neutral spatial planning - Stop general farmer subsidies, target sustainable farming only
Citizens - As consumers - As investors of their savings - As voters - As civil society	- Adjust diet towards less meat, dairy - Waste less food - Buy solar panels and/or buy green electricity (solar, wind, geothermal) - Replace fossil fuel for heating by electricity / heat pumps. - Replace fossil-driven car by electric car - Reduce water use at home (direct) and in supermarket (indirect) - Demand transparency

Who	What
Companies / producers - Primary sector (farmers, logging, mining) - Secondary sector (traders, manufacturers, food processers) - Tertiary sector (services, retailers)	- Supplier agreements - Product transparency (e.g. sustainability label to products) - Reduce direct WF - Set targets to reduce WF in supply chain (to benchmark levels) - Change supplier - Develop/commit to sustainability certification programmes - Adhere to standards for WFA
Investors - Banks - Insurance companies - Pension funds	- Include sustainability criteria in investment decisions - Create transparency (water disclosure)
NGO's	- Public campaigns to protect water resources and biodiversity
Academia	- Research into sustainable, equitable, efficient and resilient water use - More interdisciplinary research regarding connections between different domains (water-land-food-energy)
Media	- Investigative journalism, critically following govts and companies - Awareness raising
UN / international orgs	- Include sustainability criteria in international trade agreements - Collaboration towards SDG targets