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swarm

Co-funded by the Erasmus+ Programme of the European Union

Strengthening of master curricula in water resources management for the Western Balkans HEIs and stakeholders

Practical challenges of large hydropower

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Practical challenges of large hydropower

Table of contents

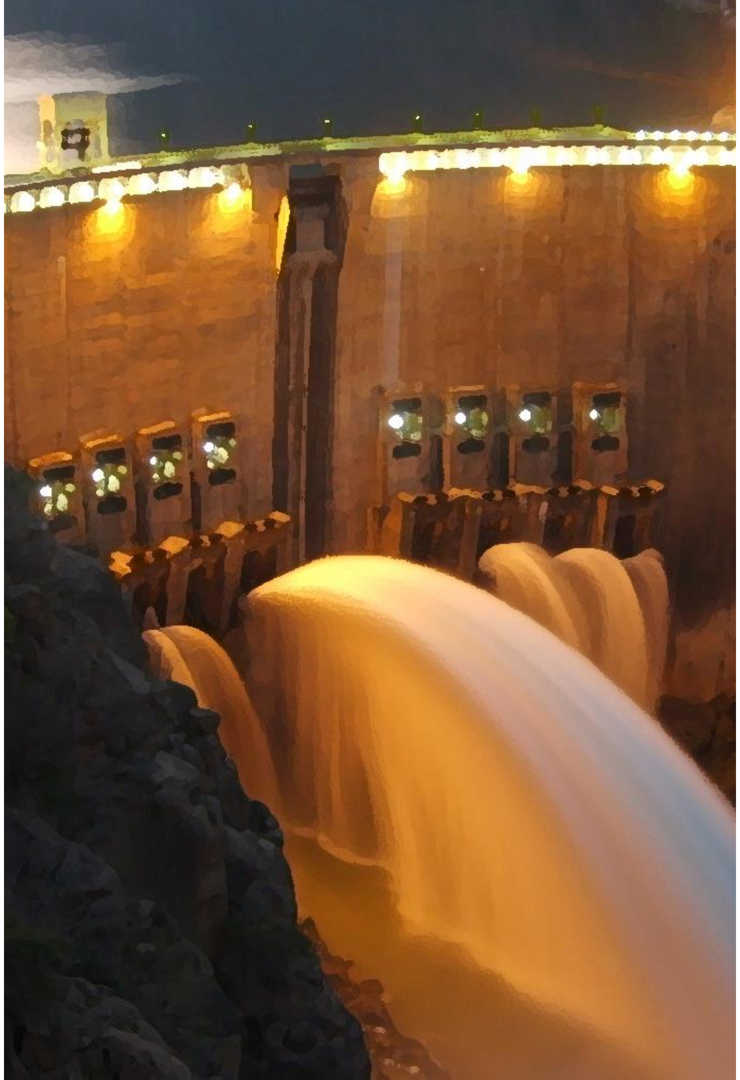
TÉCNICO LISBOA

Introduction to large hydro

Examples

Relevance

Online quiz
1-6



Introduction to large hydro

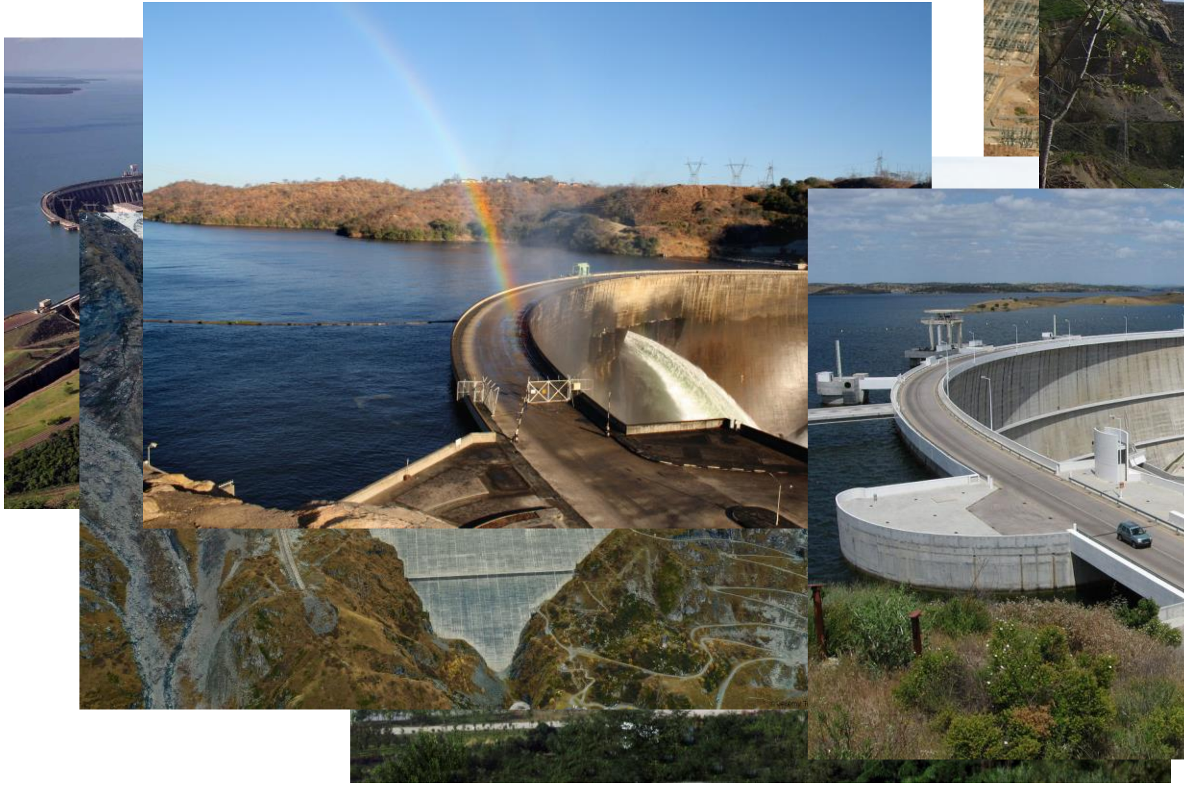
Examples of large hydro

Introduction to large hydro

Examples of large hydro

Introduction to large hydro

Examples of large hydro

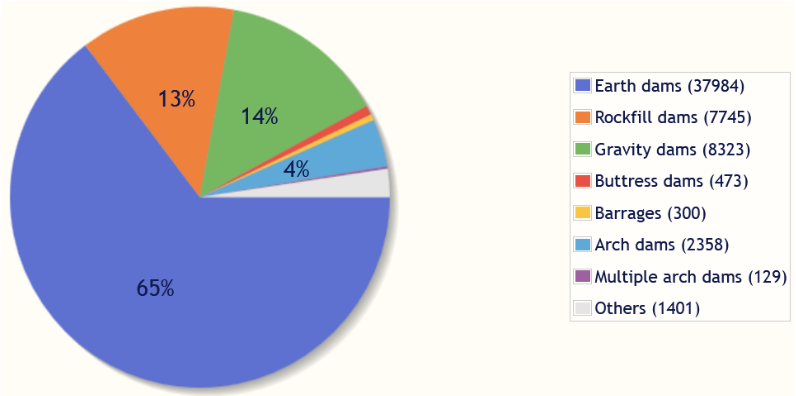


Introduction to large hydro

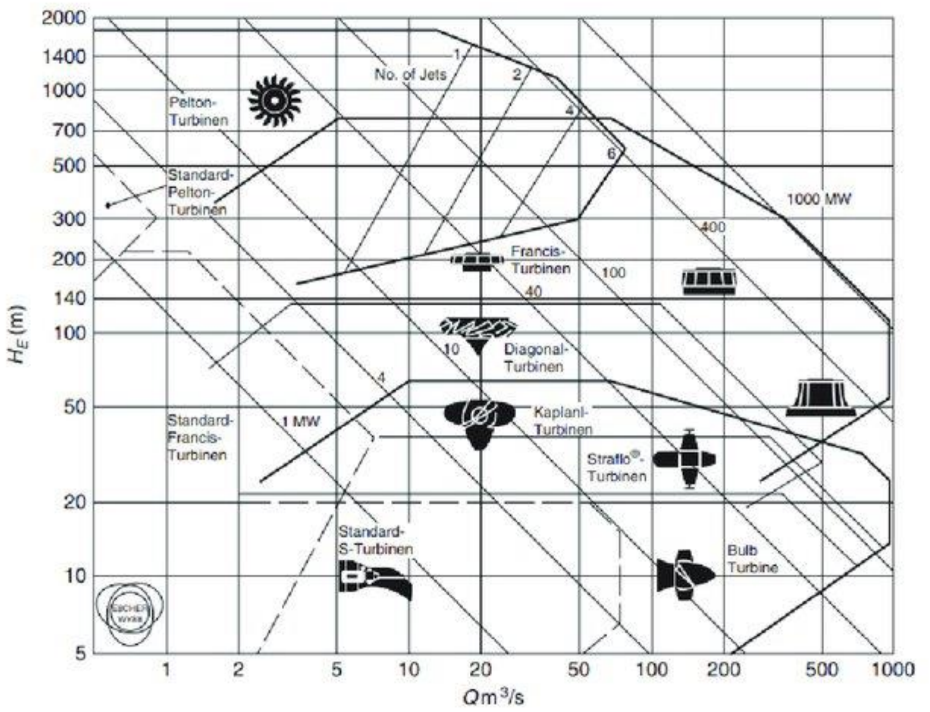
$$E = P \cdot t = Q \cdot H \cdot \gamma \cdot \mu \cdot t$$

Basic notions

- Storage vs. run-of-the-river.
- High vs. low head.
- Embankment / concrete gravity / concrete arch.



https://www.icold-cigb.org/GB/world_register



Bajracharya, Tri Ratna, Rajendra Shrestha, and Ashesh Babu Timilsina. "A Methodology for Modelling of Steady State Flow in Pelton Turbine Injectors." *Journal of the Institute of Engineering* 15.2 (2019): 246-255.

Introduction to large hydro

Basic notions

Introduction to large hydro

Relevance of large hydro

A dam with a height of 15 metres or greater from lowest foundation to crest or a dam between 5 metres and 15 metres impounding more than 3 million cubic metres.

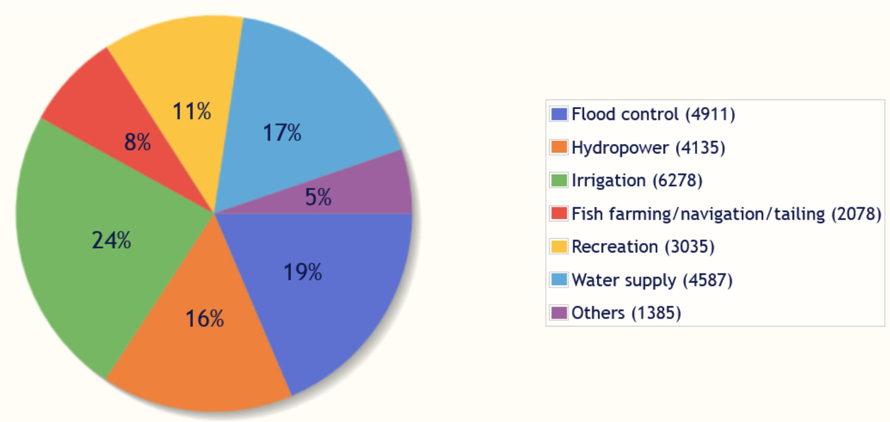
In April 2020 there were more than 58713 large dams in the world.

Dam name	Reservoir Cap. (10^3 m^3)	Resettled persons	Country
SANXIA	39 300 000	900 000	China
SANMENXIA	9 600 000	370 000	China
DANJIANGKOU	33 910 000	347 200	China
XIN'ANJIANG	21 626 000	271 550	China
XIAOLANGDI	12 650 000	175 600	China
KUIBYSHEV	58 000 000	150 000	Russia (Russian Fed.)
ZHEXI	3 570 000	139 522	China
RYBINSK	25 400 000	116 700	Russia (Russian Fed.)
MANGLA	9 120 000	110 000	Pakistan
WUQIANGXI	4 350 000	107 048	China
XINFENGJIANG	13 896 000	106 000	China
CHANGMA	194 000	96 000	China
XIANGJIABA	5 185 000	89 800	China
XIJIN	3 000 000	89 323	China
LONGTAN	29 920 000	75 100	China
ROSEIRES	1 250 000	70 000	Sudan
BAIHETAN (C)	18 800 000	69 000	China
SHUIKOU	2 340 000	67 239	China
HUALIANGTING	2 398 000	61 124	China
VOTKINSK	9 400 000	61 000	Russia (Russian Fed.)

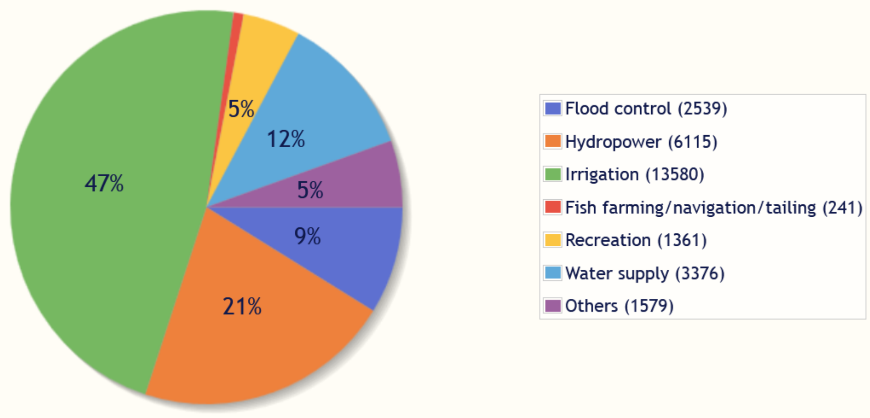
https://www.icold-cigb.org/GB/world_register

Introduction to large hydro

Relevance of large hydro



Multi-purpose



Single-purpose

https://www.icold-cigb.org/GB/world_register

Introduction to large hydro

Relevance of large hydro

- The peak of construction of large dams has clearly passed.
  - Because in many places there are no more technically feasible locations.
  - Because other sources of energy have emerged.

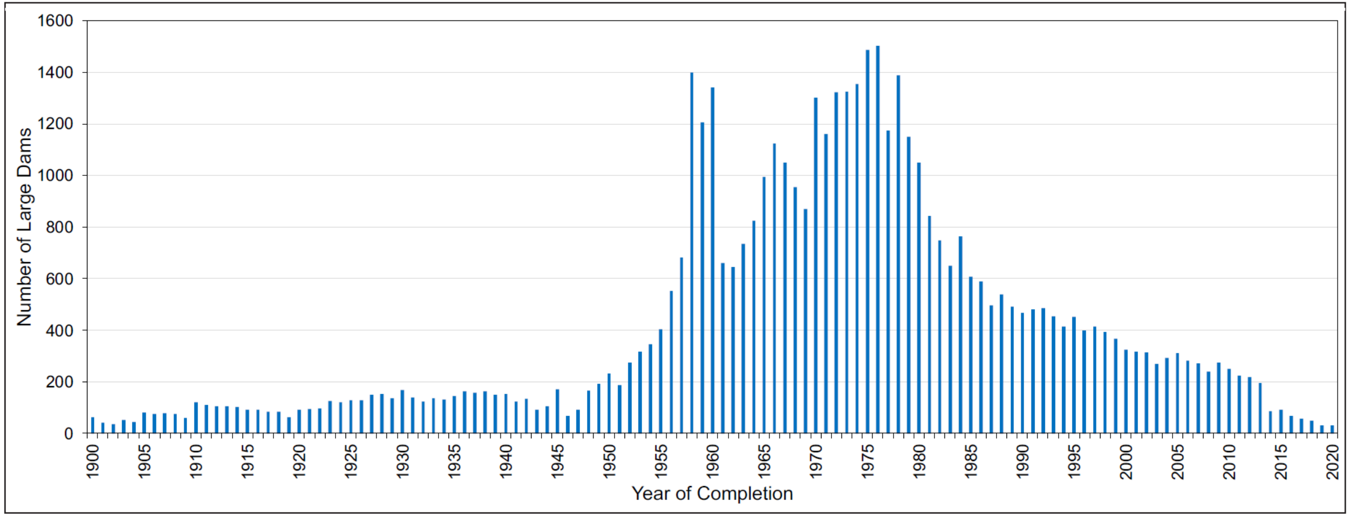
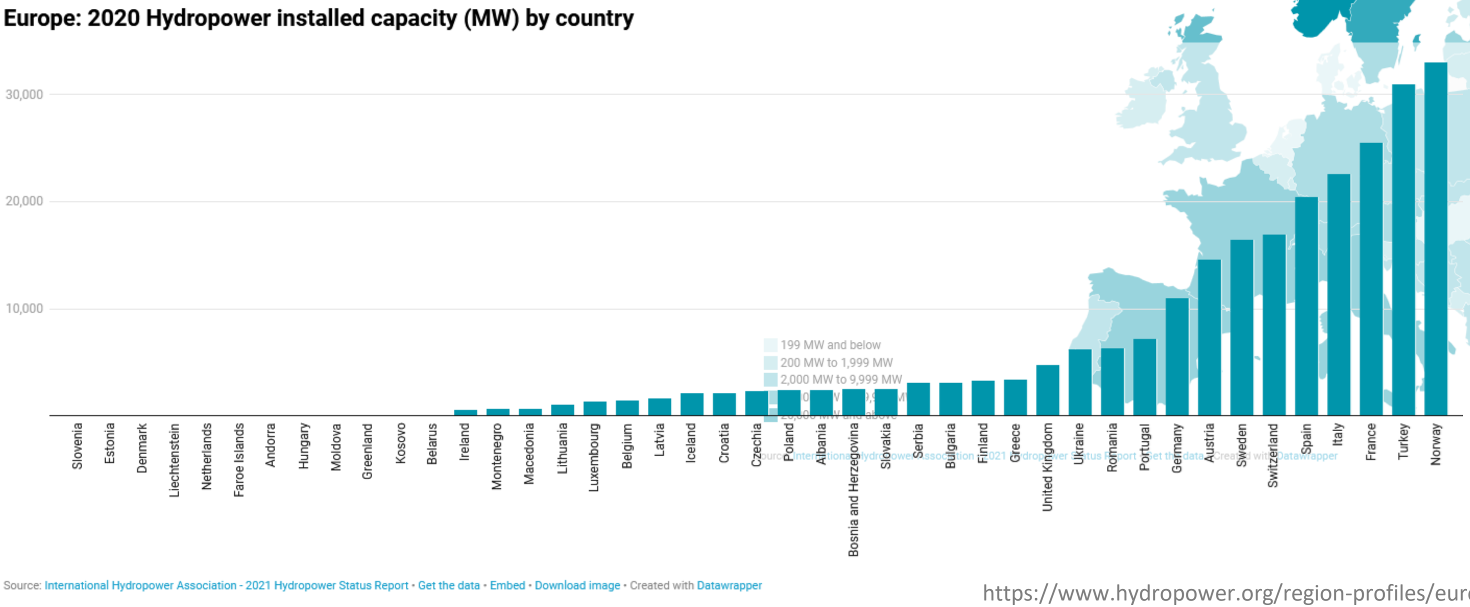
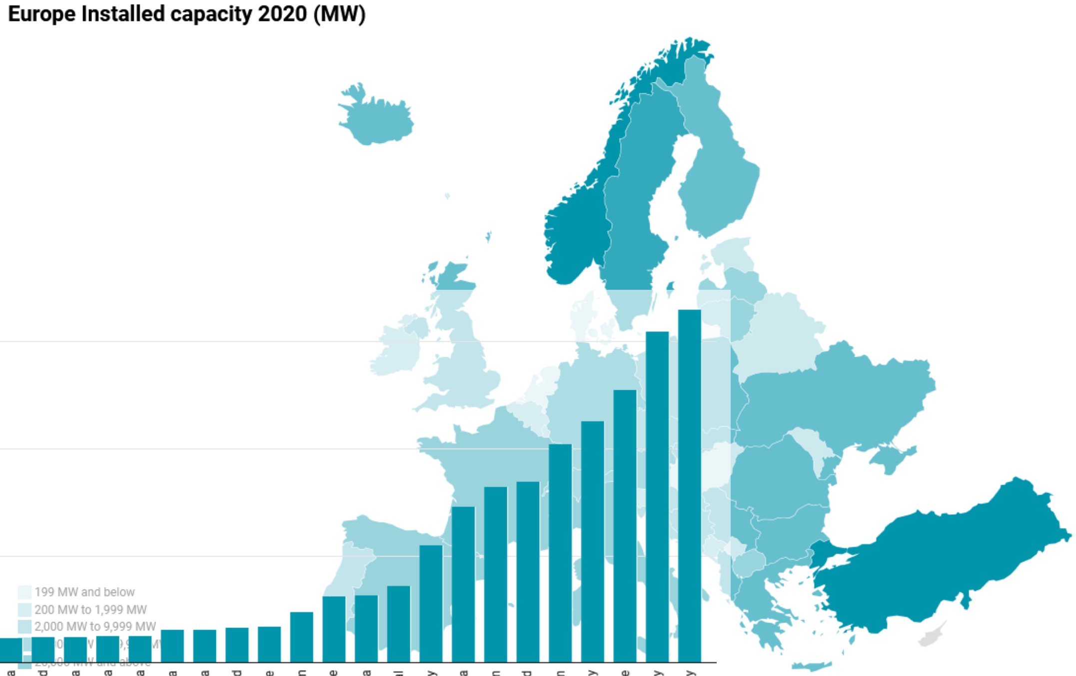


Figure 1. Annual construction of large dams globally since 1900 (Data source: ICOLD WRD, 2020)

Introduction to large hydro

Relevance of large hydro

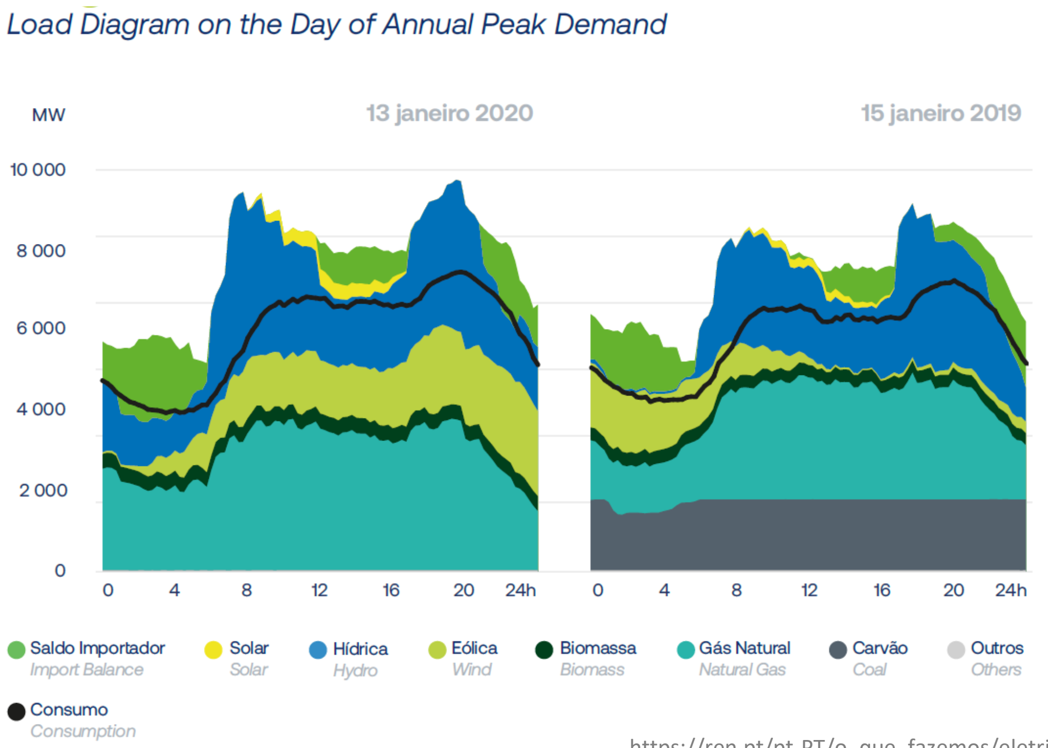




https://www.hydropower.org/region-profiles/europe 2022.04.11

Introduction to large hydro

Relevance of large hydro

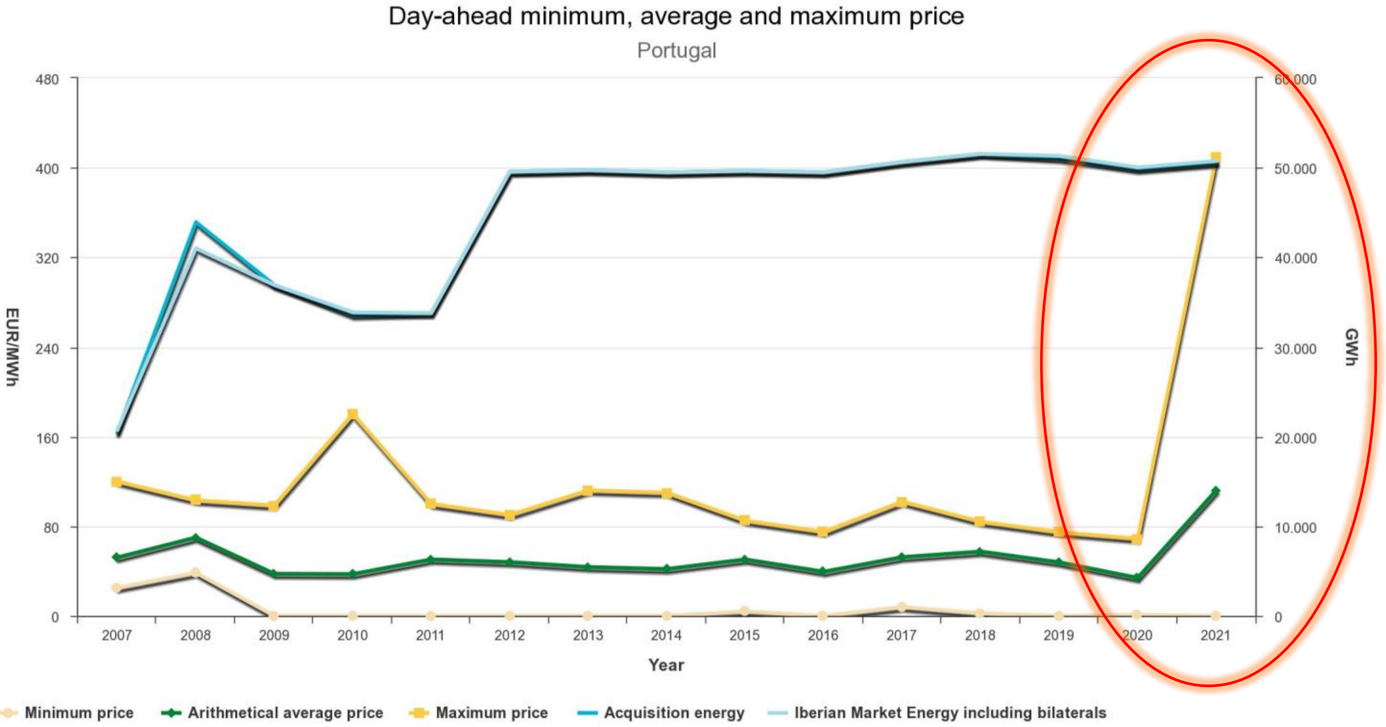


Online quiz 7-11

https://ren.pt/pt-PT/o_que_fazemos/eletricidade/

Introduction to large hydro

Relevance of large hydro



• The data of 2007 make reference to the period July-December.

https://www.omie.es/en/market-results/interannual/daily-market/daily-prices?scope=interannual&system=2

Introduction to large hydro

Relevance of large hydro

- Large hydro is relatively expensive and displays a slow return on investment.
- Safety concerns are legitimate.
- There are environmental and social issues that must be addressed.
- Without large hydro it is difficult to store water (e.g., for drinking water supply or agriculture).
- Large (and small) hydro still have a major role in energy production in certain regions.
- It can be used to stabilize electricity grids like almost no other technology.

Building a dam

Data collection

About licensing and investment

Design and construction

Building a dam

Data collection

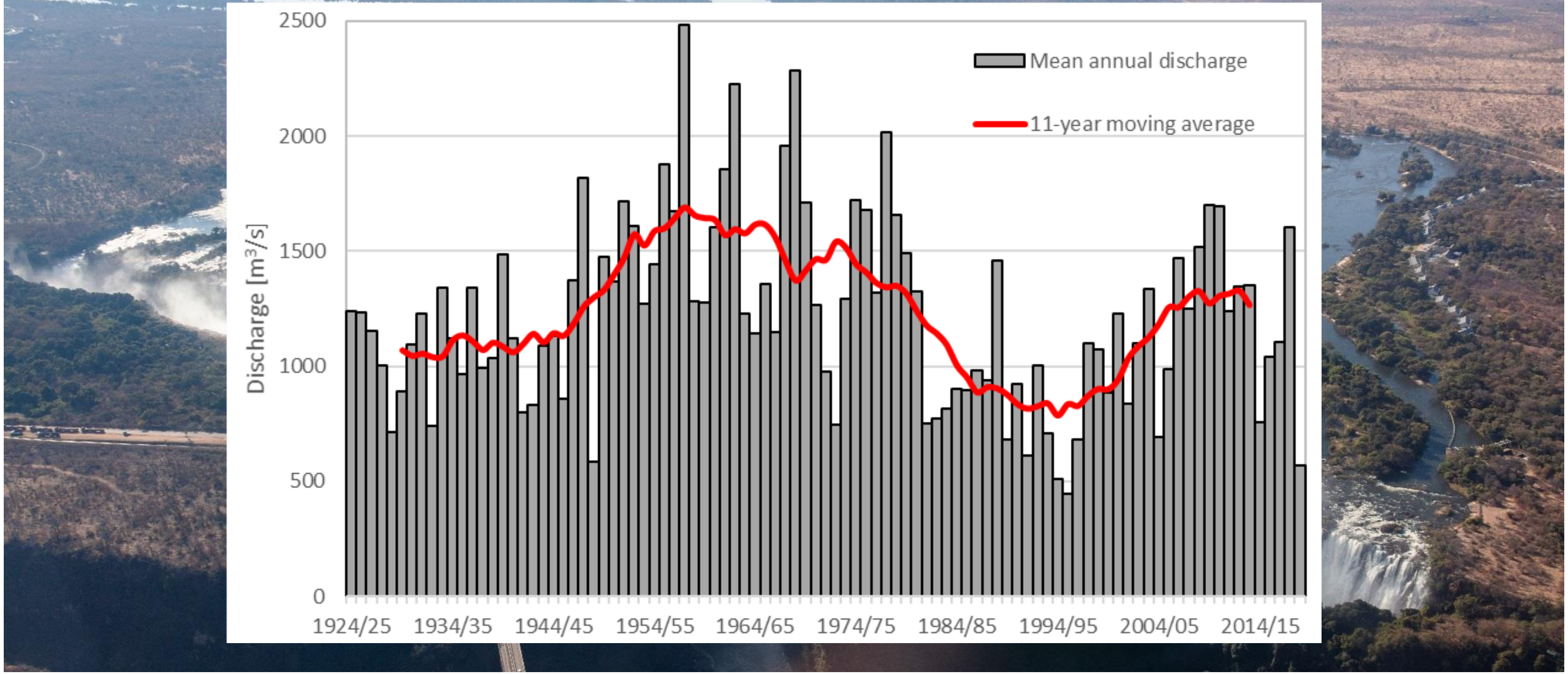
- Essential for sound design and avoiding “surprises”.

- Water availability.
- Extreme events.
- Geological conditions.
- Sediment transport.
- Environmental concerns.
- Climate change (glaciers).

Building a dam

Data collection

- The Zambezi River Basin at Victoria Falls.



Building a dam

About licensing and investment

- Long-term commitment with a slow return on investment.
- Capital-intensive endeavor, often with the support of international institutions (World Bank, EBRD, AfDB, ADB, etc.) or private investors.
- Licensing requires that a project is developed to a large extent, and substantial investment is required before it is even obtained.
- The whole process can take decades. It is not uncommon that phases / activities overlap each other.

- This is challenging and can lead to “cutting corners”.

Operating a hydropower system

Drivers of the operation

Droughts and long-term reliability

Floods

Sediment management

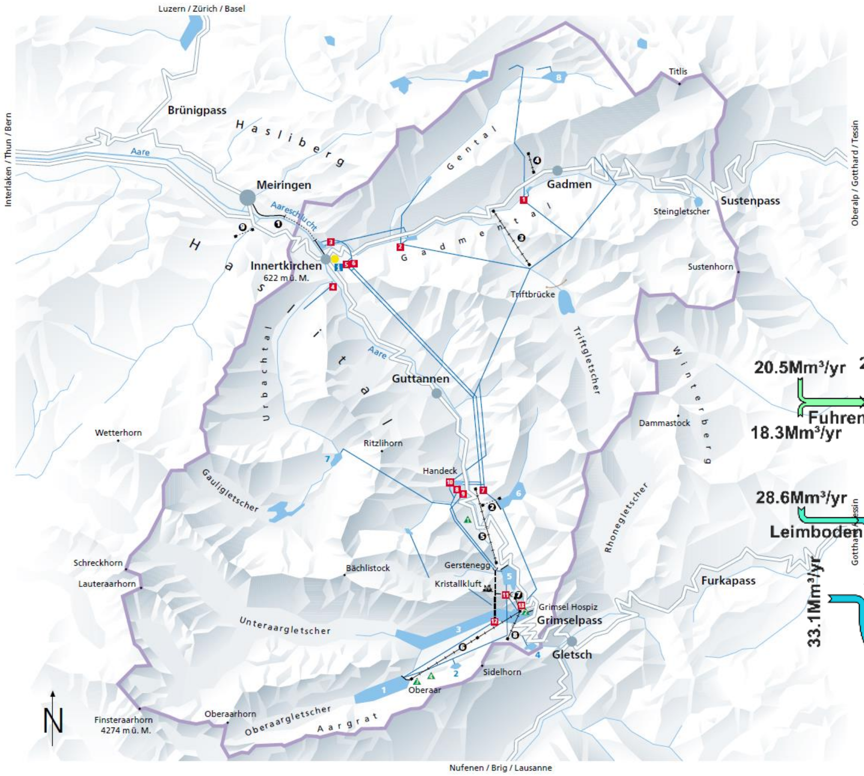
Operating a hydropower system

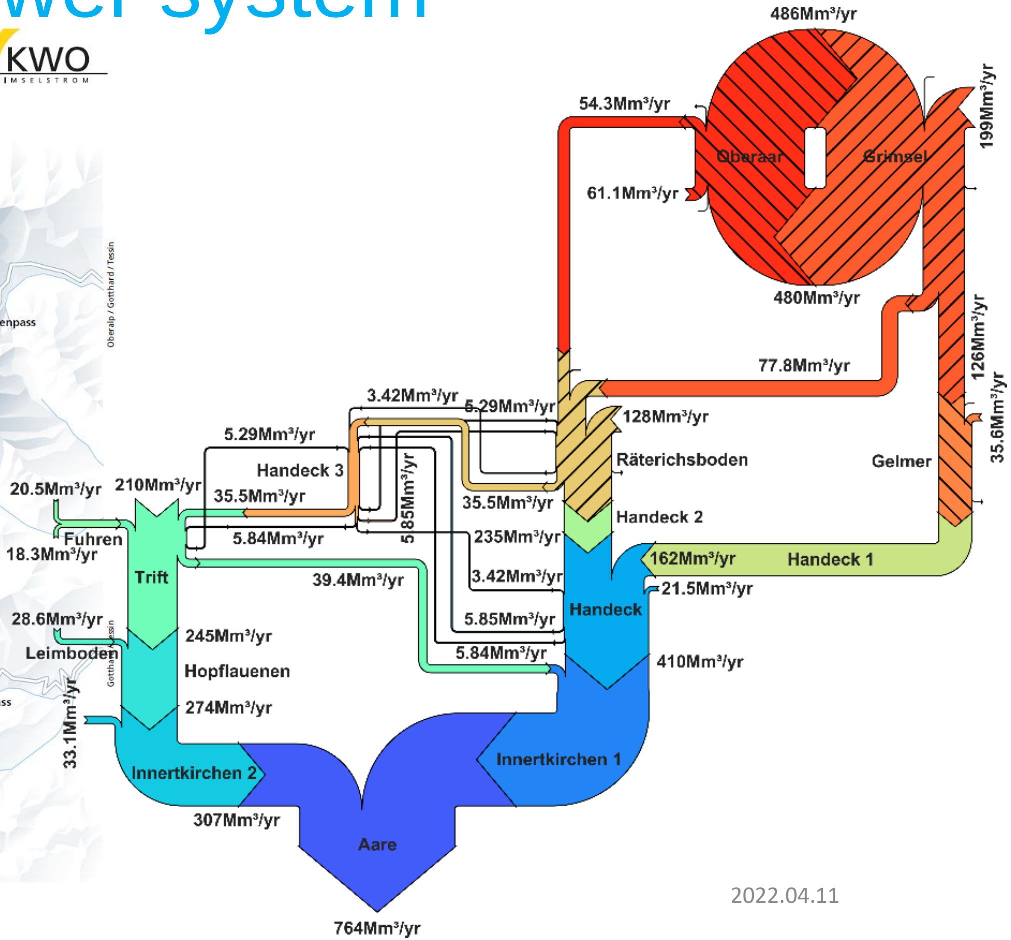
Drivers of the operation

- Safety (preventing failures at all costs);
- Fulfilling its goals (e.g., hydropower production or storage for irrigation or water supply);
- Maximizing profits;
- Ensuring long-term sustainability:
  - Sediment management;
  - Rehabilitation whenever required;
  - Retrofitting.
- Very often dam operations can be anything but simple.

Operating a hydropower system

Drivers of the operation

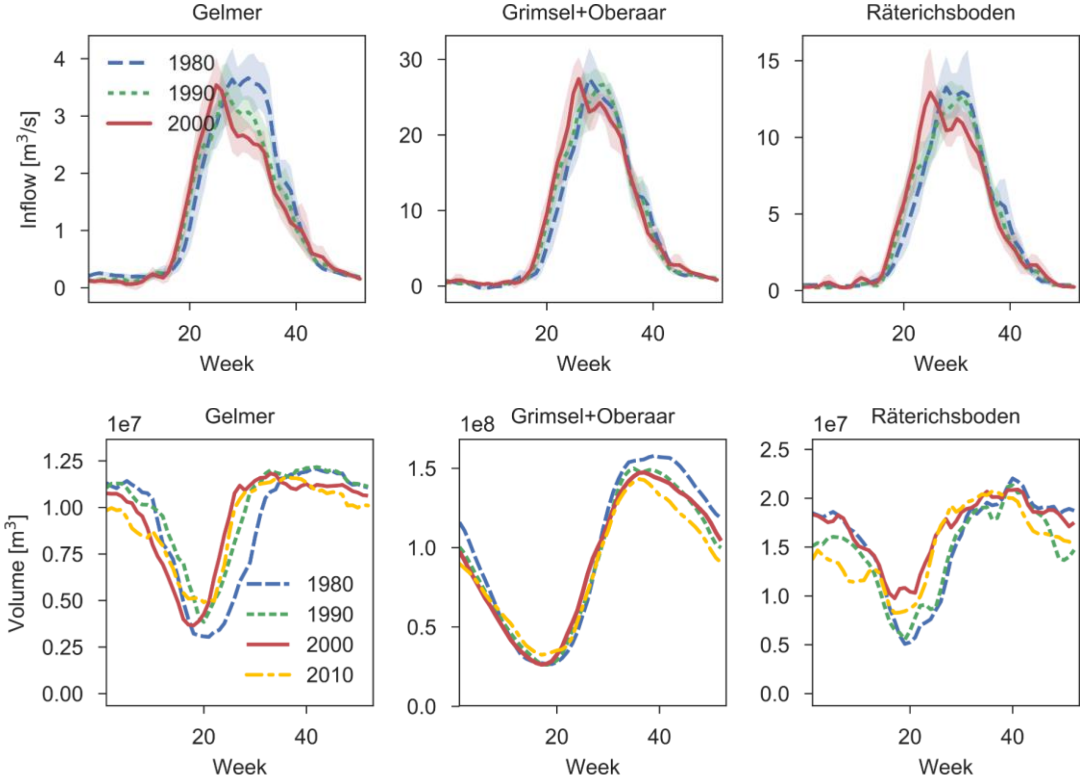




Operating a hydropower system

Drivers of the operation

- Seasonal operation
  - Summer inflows.

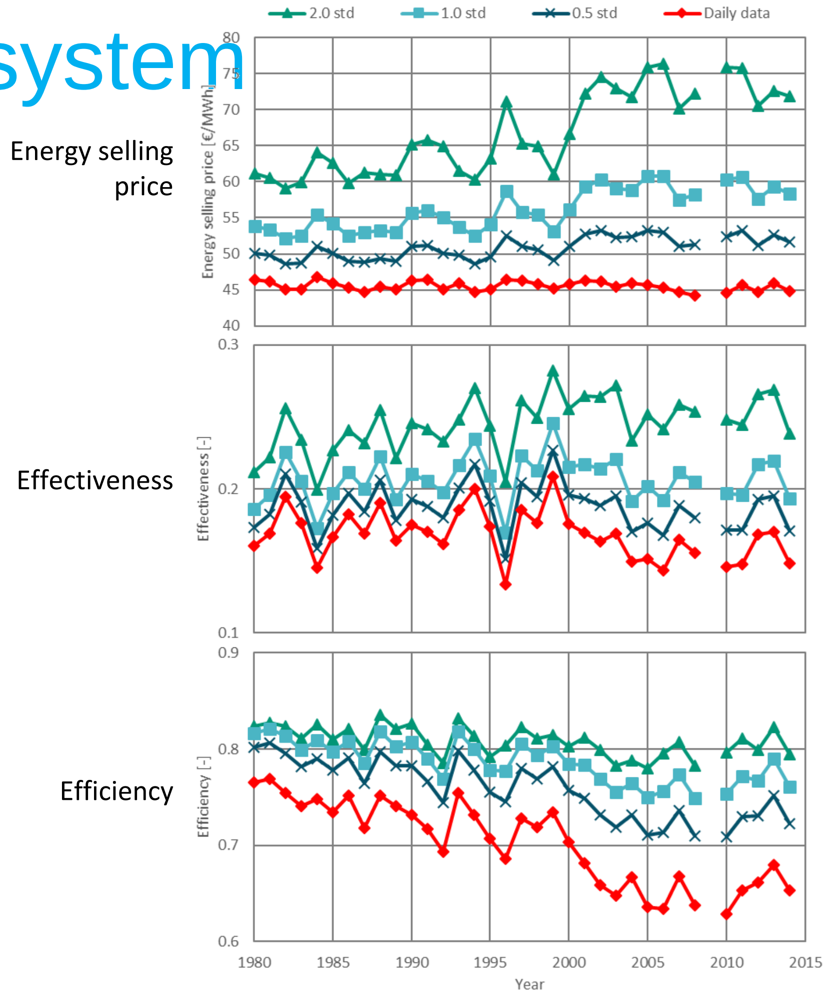


https://commons.wikimedia.org/wiki/File:Grimselpass.jpg

Operating a hydropower system

Drivers of the operation

- Three metrics analyzed the changes in the system.
  - Effectiveness: how much of the system potential is being used (no water and no storage limitations).
  - Efficiency: how “well” are the water resources being used (no storage limitations).
  - Energy selling price.



Operating a hydropower system

Drivers of the operation

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    used (no wate
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  - Efficiency: how
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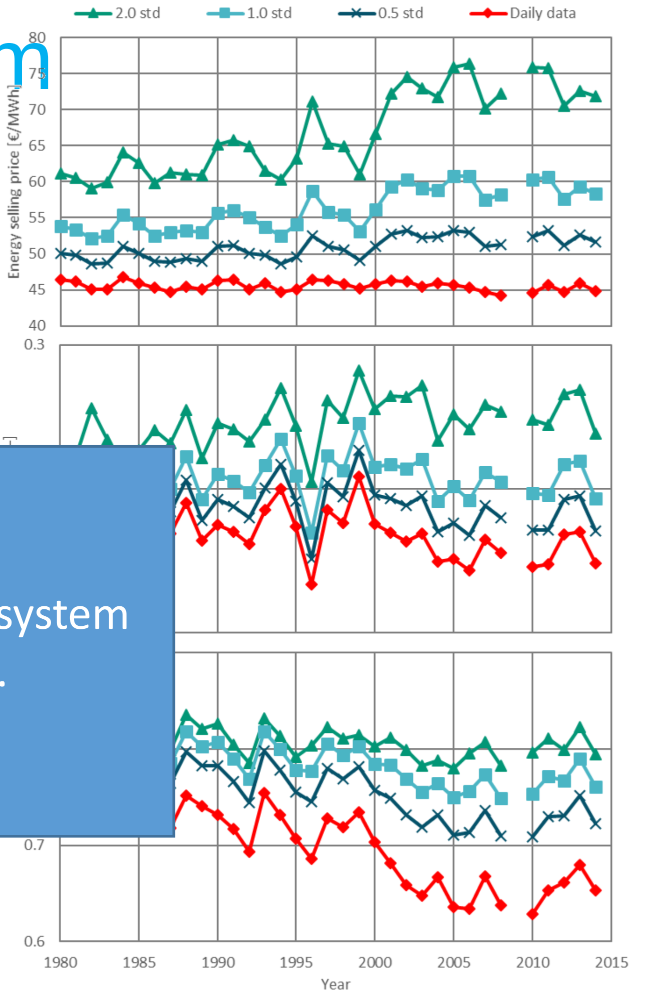
  - Energy selling price.

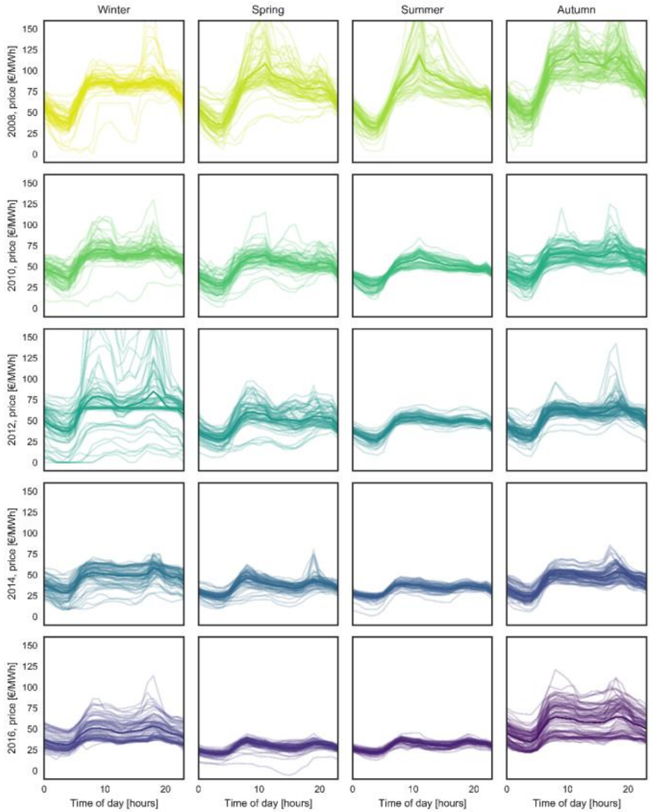
Energy selling price

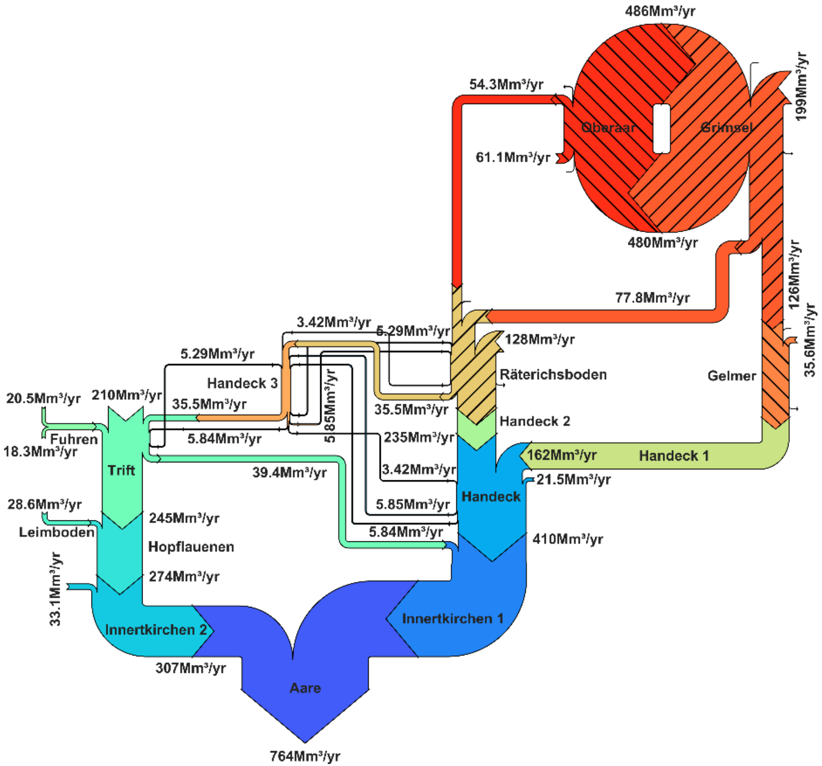


The driver of “upgrades” to the system has clearly been sub-daily.

Operating a hydropower system

Drivers of the operation

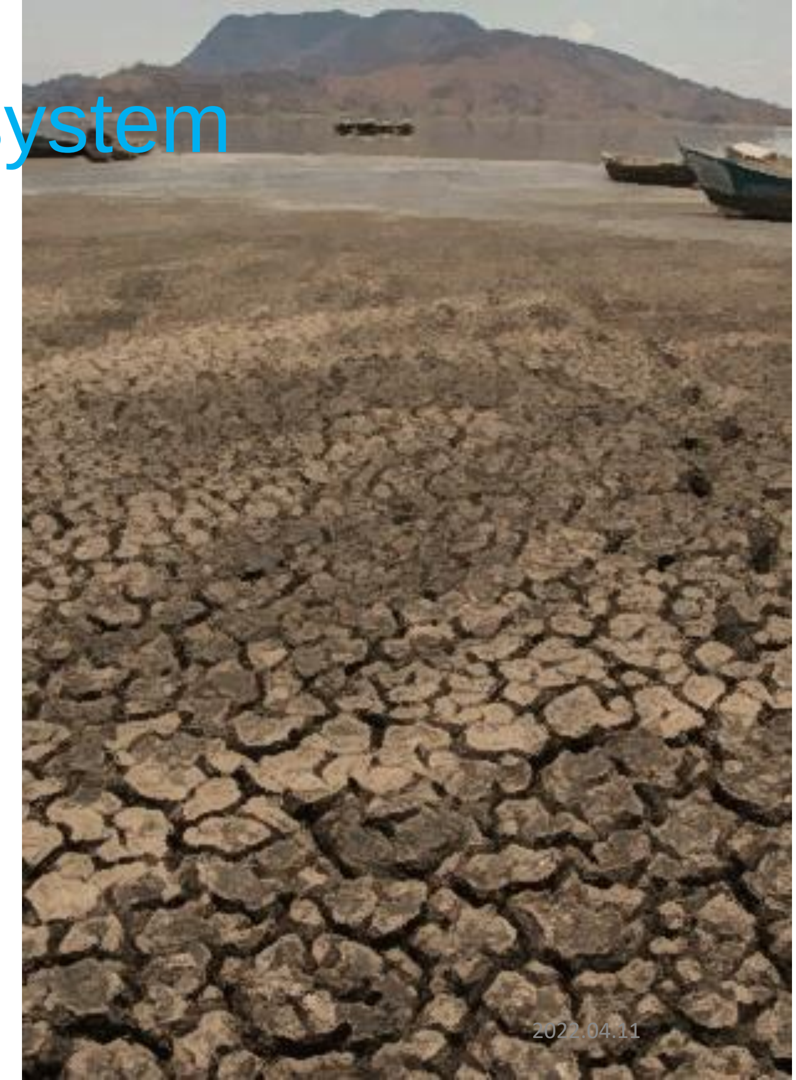




Operating a hydropower system

Droughts and long-term reliability

- One of the key capabilities of dams (or rather, the reservoirs they hold) is to “transfer” water from wet periods to dry ones.
- This is done at a cost (evaporation) and has limits (active volume).
- Mis-management of reservoirs (or “bad luck”) can result in critical water shortages.



Operating a hydropower system

Droughts and long-term reliability

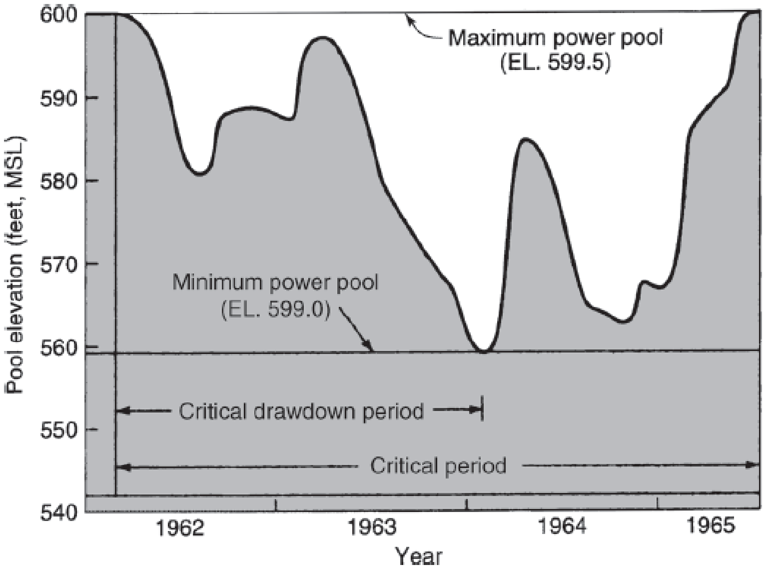


Figure 17.7.3

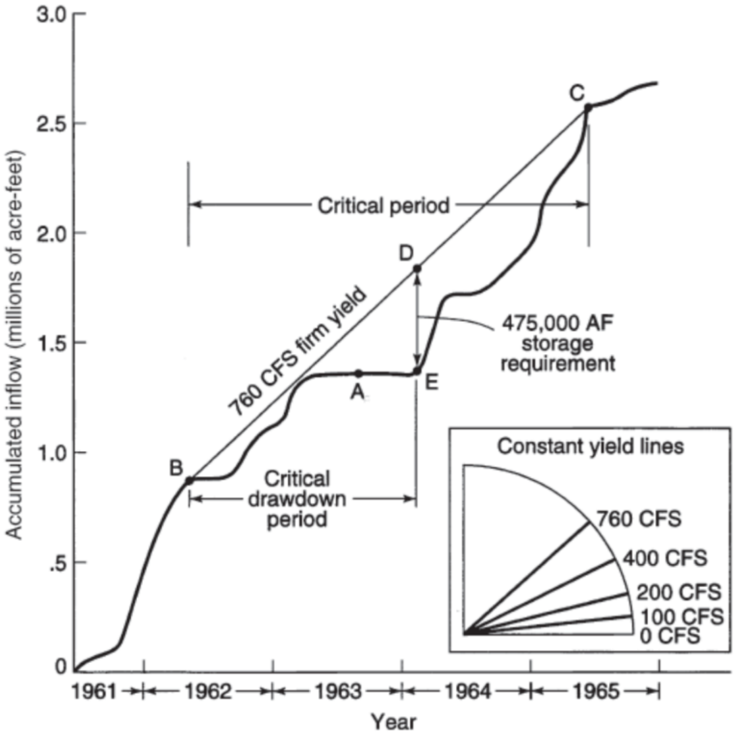
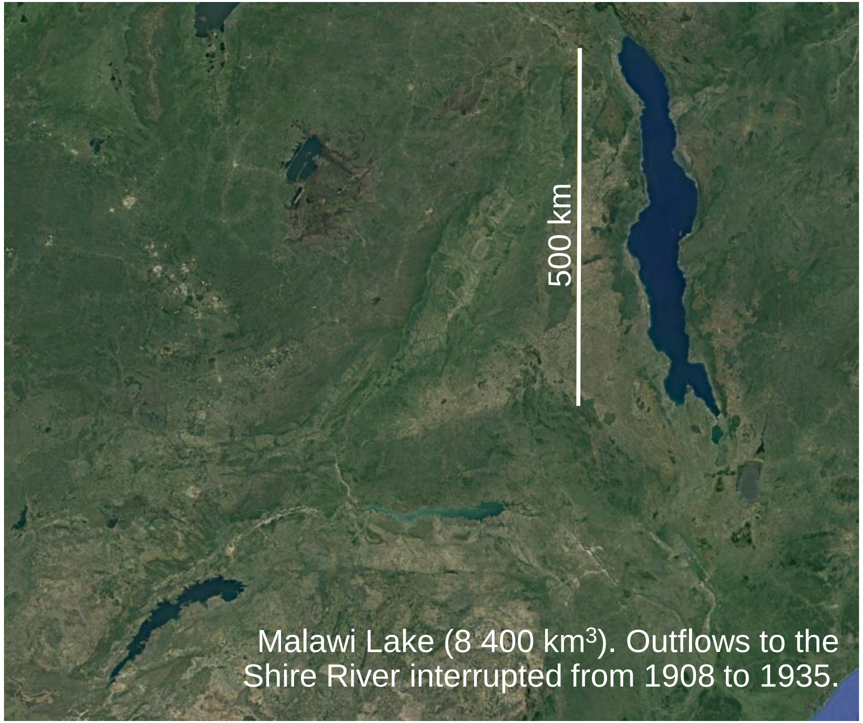


Figure 17.7.4 Mass curve and constant yield lines (from U.S. Army Corps of Engineers, 1977).

Larry W. Mays. Water Resources Engineering, 3rd edition (Wiley, 2019). Chapter 17.

Operating a hydropower system

Droughts and long-term reliability



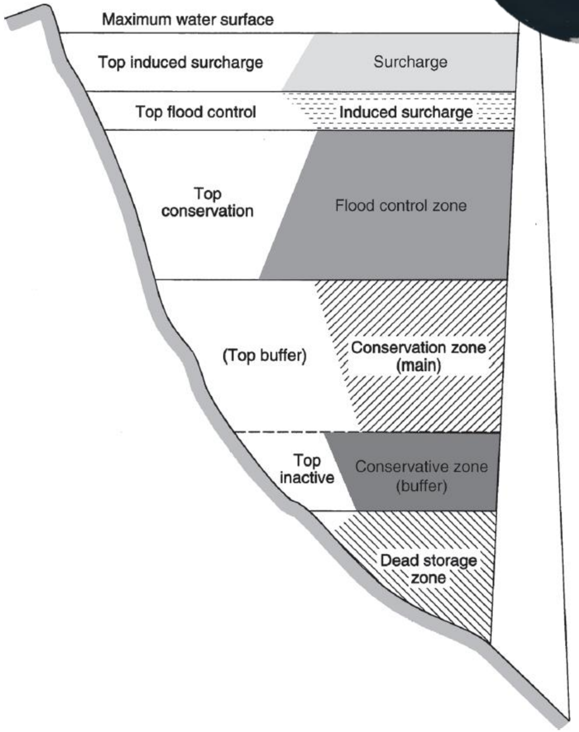


Figure 17.7.1 Reservoir storage allocation zones (from U.S. Army Corps of Engineers (1977)).

https://openknowledge.worldbank.org/handle/10986/14649

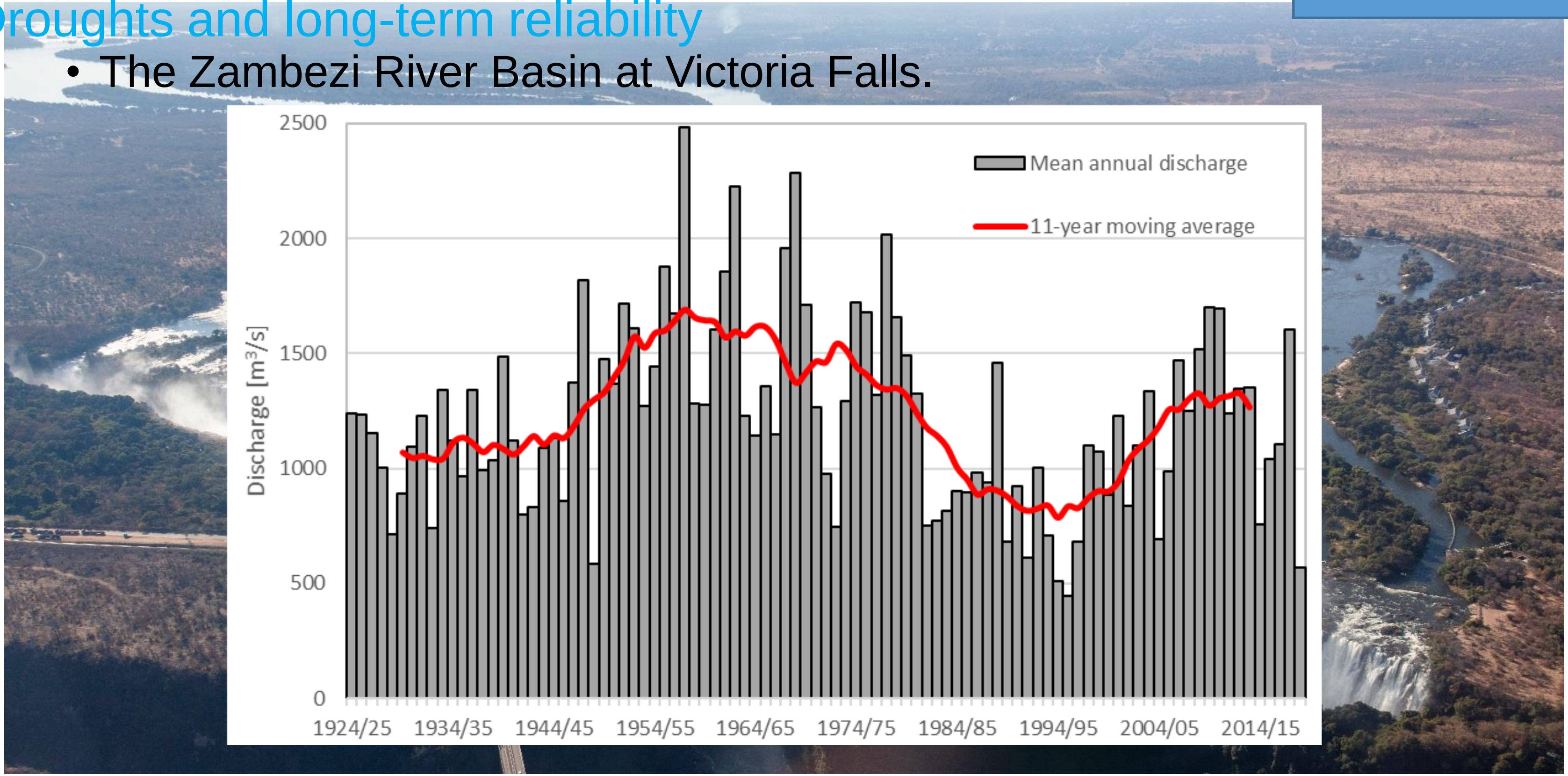
K. Sene, et al.; Long-term variations in the net inflow record for Lake Malawi. Hydrology Research 1 June 2017; 48 (3): 851–866

Operating a hydropower system

Again !

Droughts and long-term reliability

- The Zambezi River Basin at Victoria Falls.



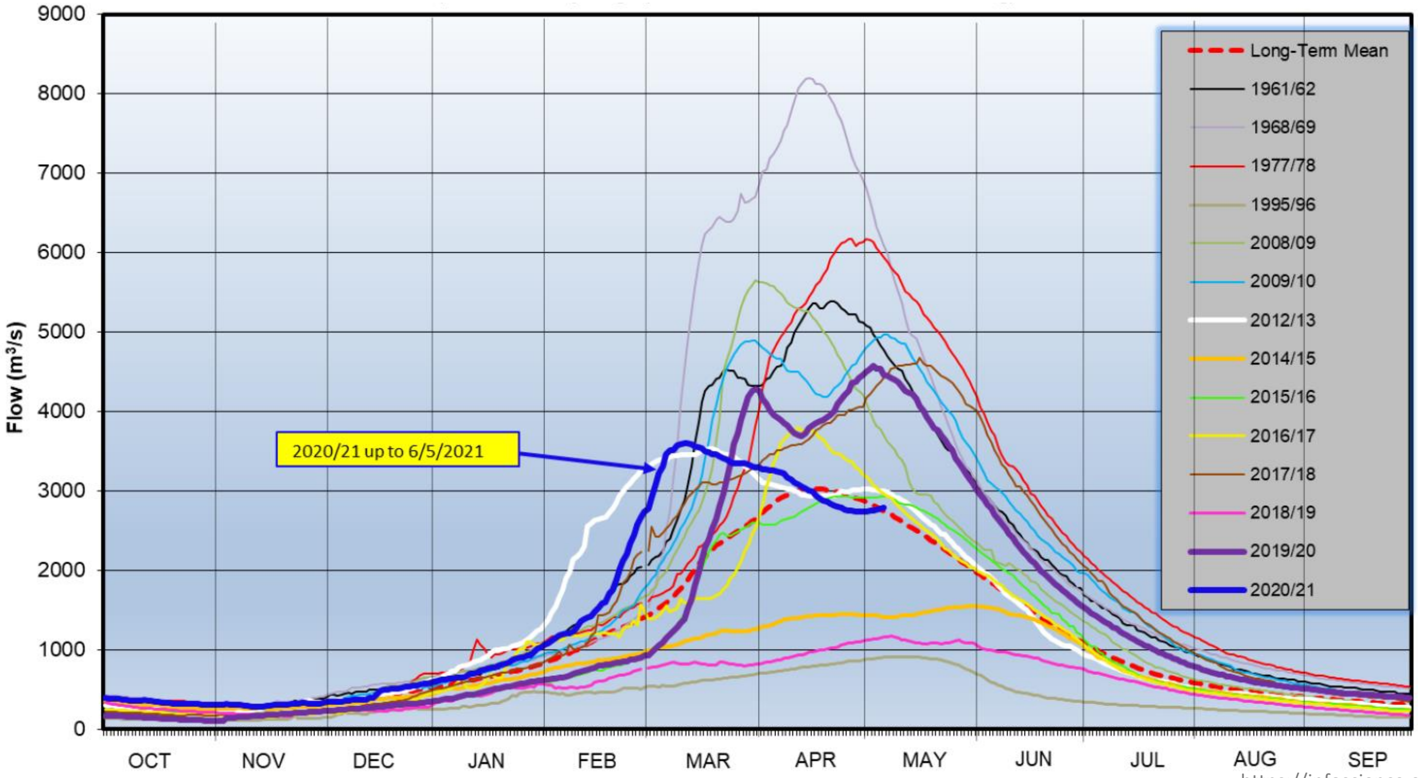
Operating a hydropower system

Droughts and long-term reliability

- The case of the Kariba reservoir.
- Largest man-made reservoir in the world by volume (180 km^3).
- Used mostly for hydropower production.
- Its importance to the regional economy (Zambia and Zimbabwe) cannot be overstated.

Operating a hydropower system

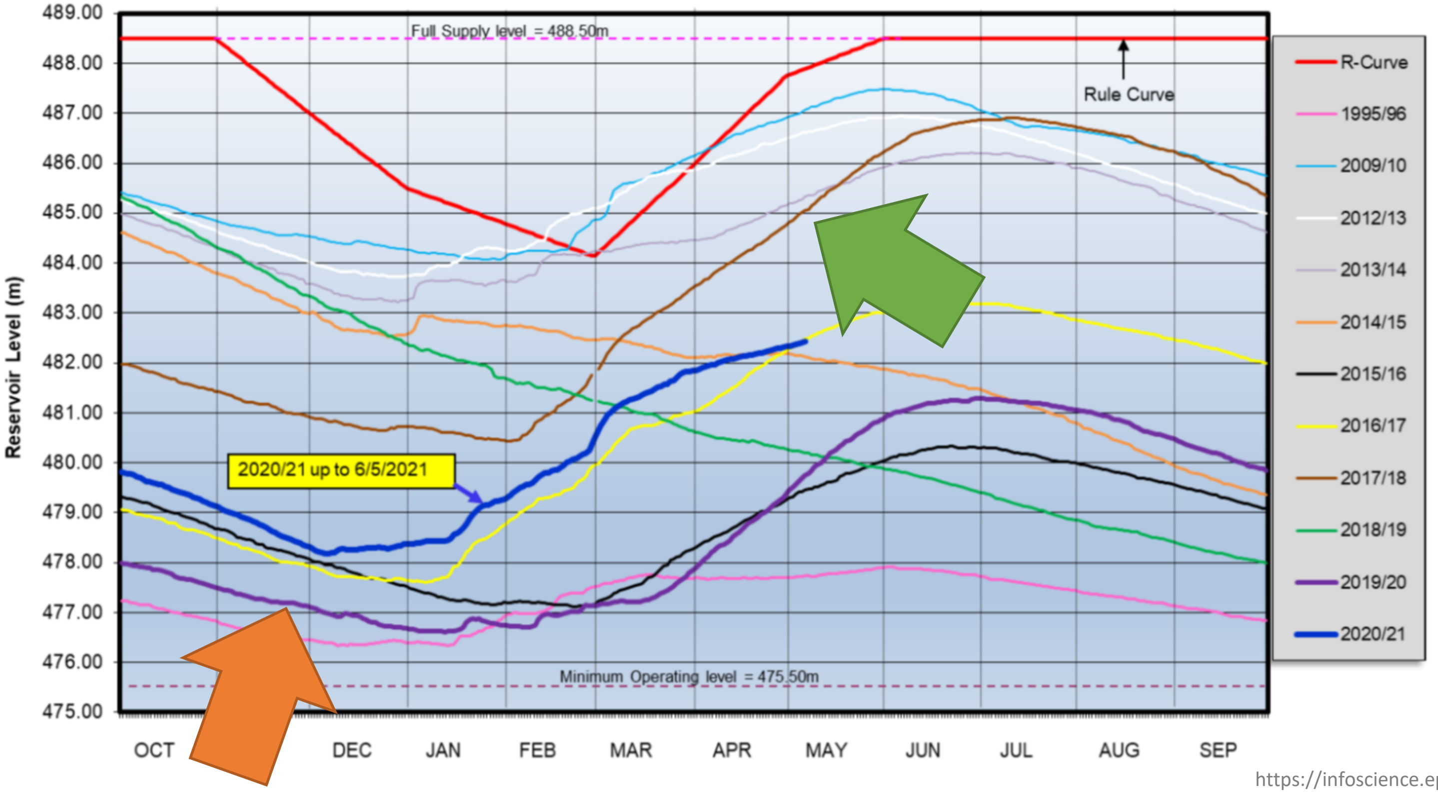
Droughts and long-term reliability



http://www.zambezira.org
https://infoscience.epfl.ch/record/201642?ln=en
Noret, C., Girard, J.-C., Munodawafa, M.C., Mazvidza, D.Z., 2013. Kariba dam on Zambezi river: stabilizing the natural plunge pool. La Houille Blanche, 34-41.

Operating a hydropower system

Droughts and long-term reliability



http://www.zambezira.org

https://infoscience.epfl.ch/record/201642?ln=en

Noret, C., Girard, J.-C., Munodawafa, M.C., Mazvidza, D.Z., 2013. Kariba dam on Zambezi river: stabilizing the natural plunge pool. La Houille Blanche, 34-41.

Operating a hydropower system

Floods

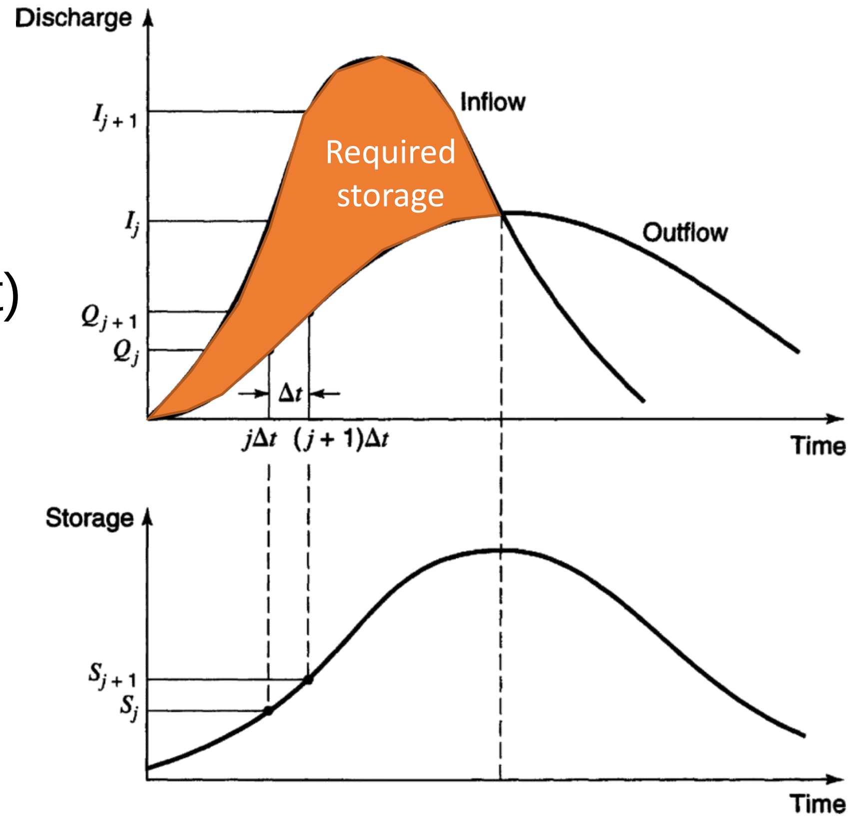
- Floods are a big issue.
  - Fortunately, they are rare.

- Dams can be used to “laminate floods”, but how this works in practice is very complex.

Operating a hydropower system

Floods

- Flood lamination.
  - Lamination effect (Qin – Qout)
  - Necessary storage.

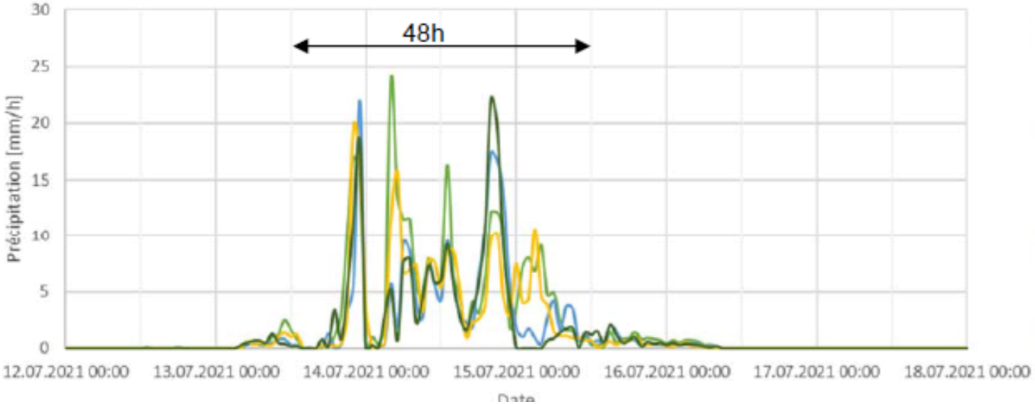


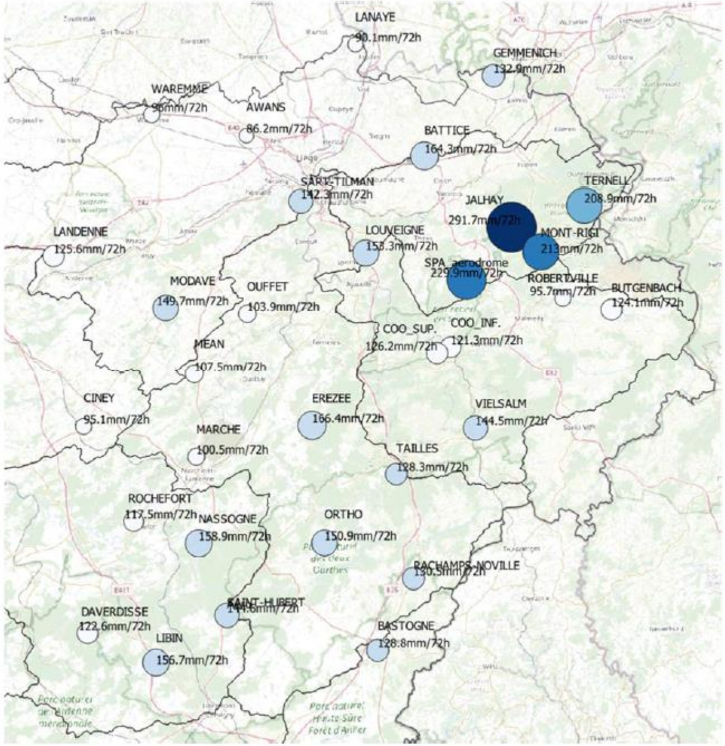
Larry W. Mays. Water Resources Engineering, 3rd edition (Wiley, 2019). Chapter 9.

Operating a hydropower system

Floods

- Example of the July 2021 floods in Central Europe. A look at Wallonia, where 39 lives where lost.





https://www.wallonie.be/fr/inondations/commissariat-special-la-reconstruction/rapport-de-lanalyse-independante-sur-la-gestion-des-voies-hydrauliques-1er-volet

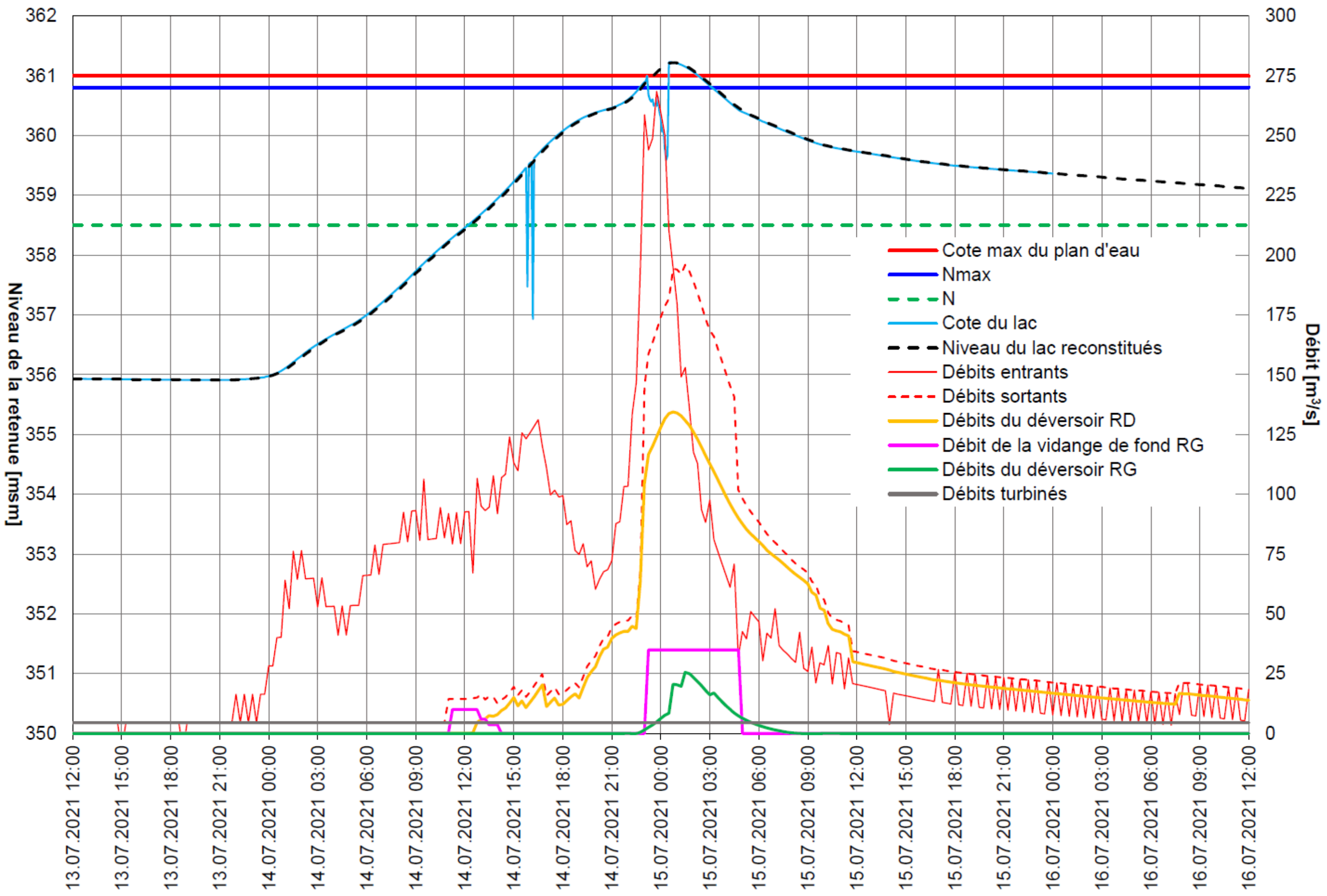
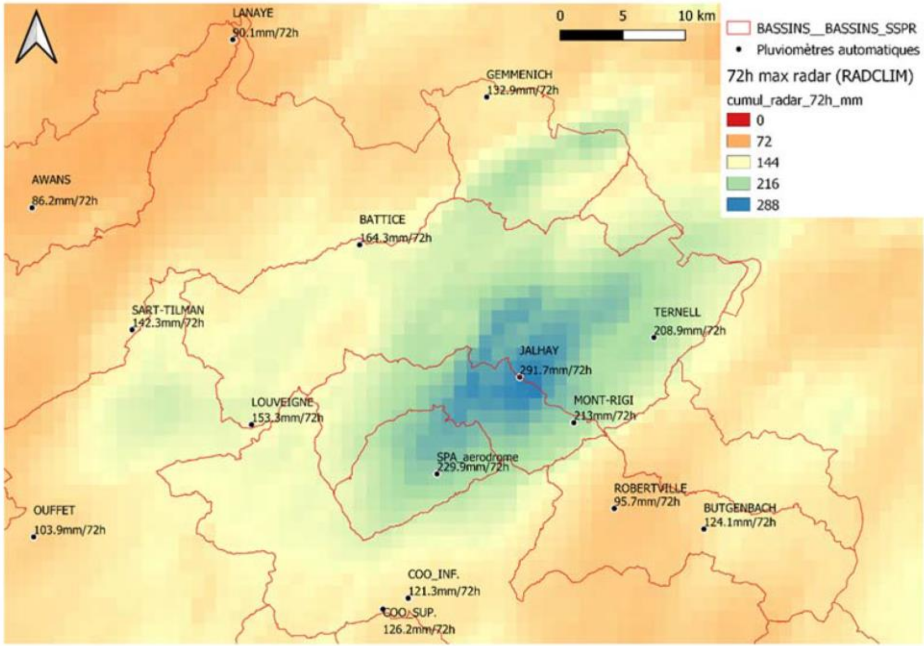
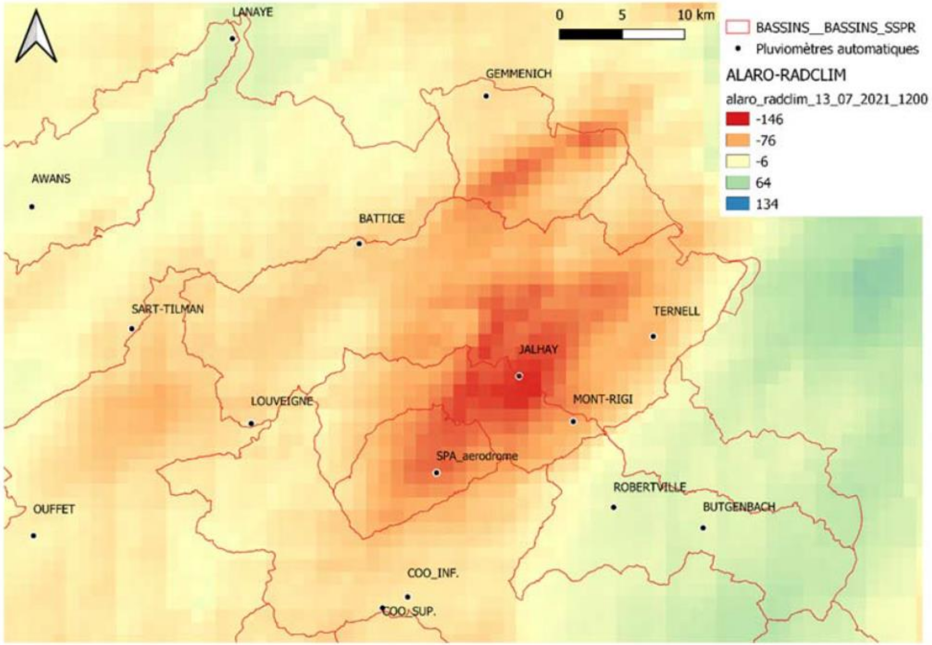


Figure 5-51 : Evolution du niveau du lac mesuré au barrage d'Eupen, des débits entrants reconstitués et des débits sortants calculés lors de la crue du 14 juillet 2021

Operating a hydropower system

Floods



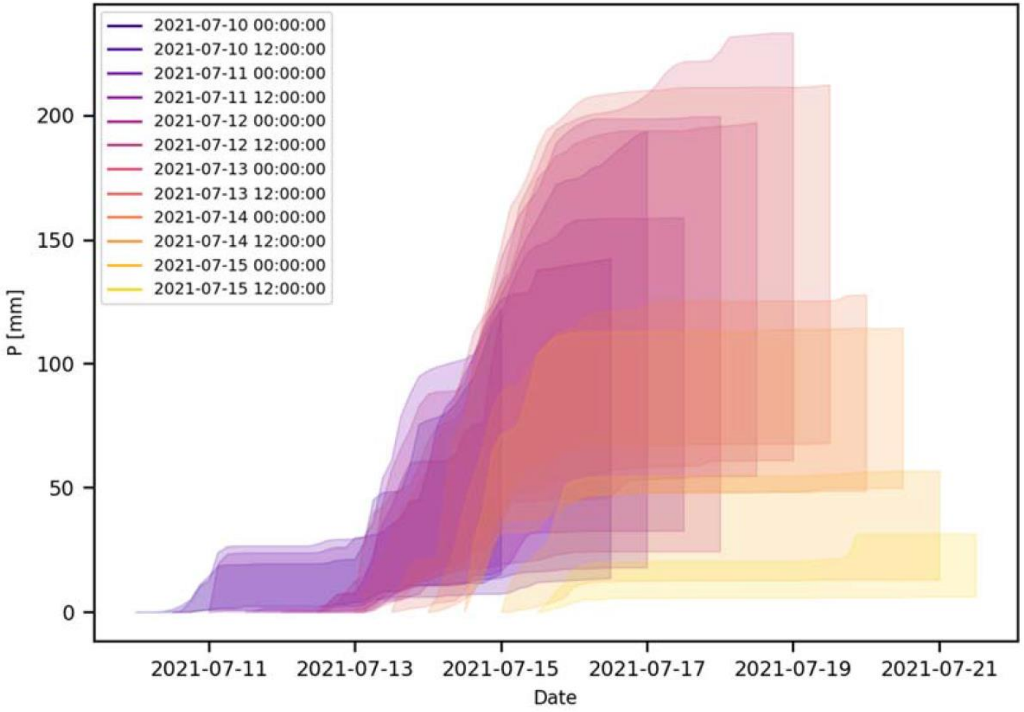


Operating a hydropower system

Floods

- In theory, the catastrophe could have been prevented.

- In practice… This is extremely hard to do.
- Difficult decisions have to be made quickly and under extreme uncertainty.



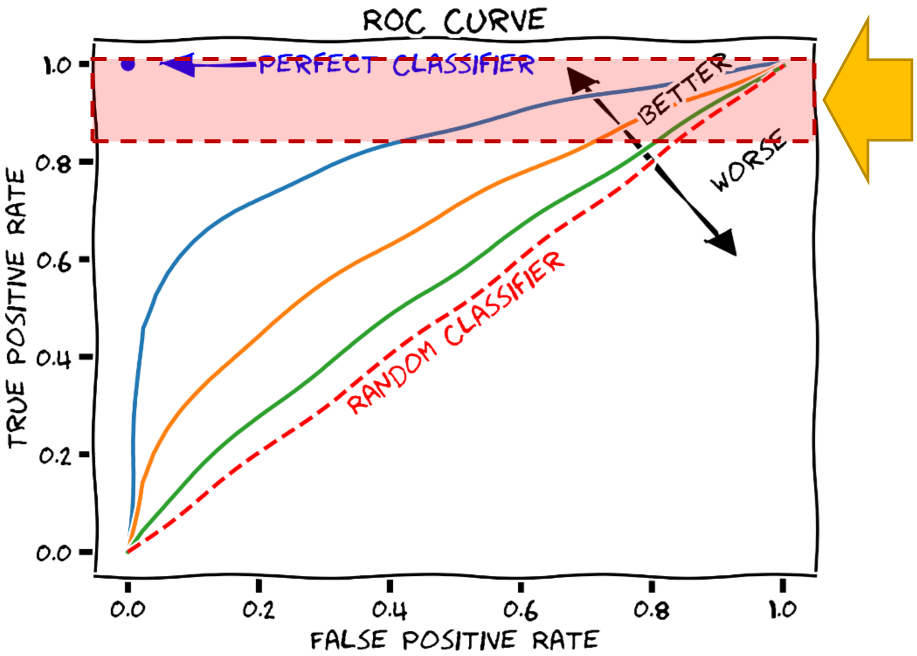
Online quiz 12-13

Operating a hydropower system

Floods

- Difficult decisions have to be made quickly and under extreme uncertainty.
- The receiver operating characteristic (ROC) can help.

A flood is expected and it comes



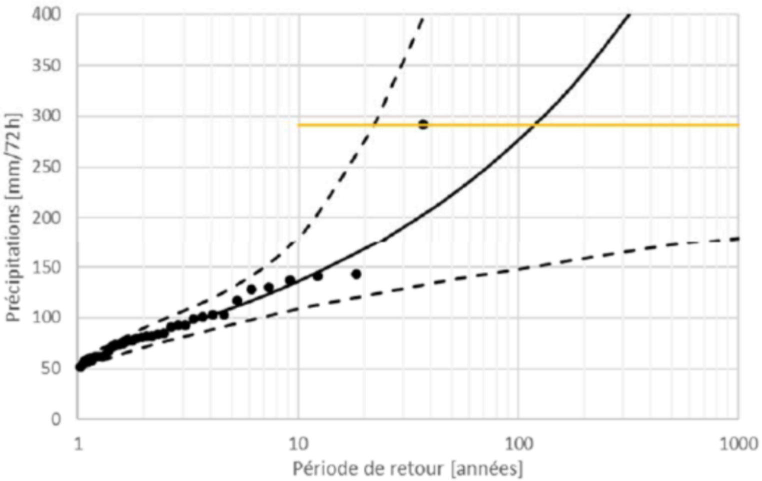
A flood is expected and no flood comes.

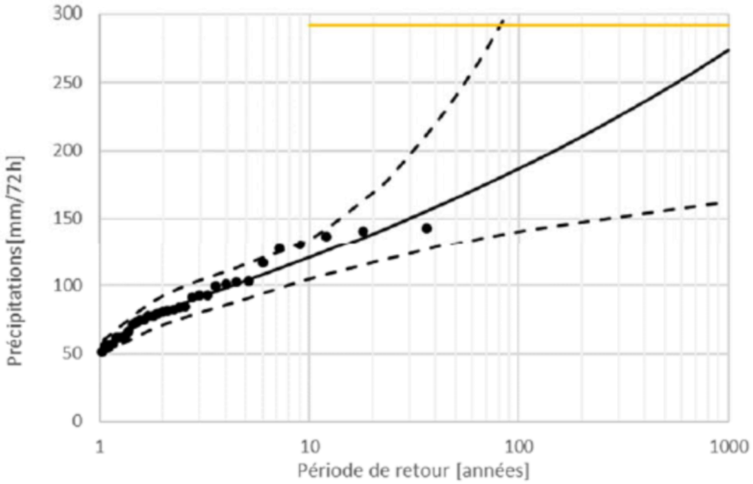
Martin Thoma. https://commons.wikimedia.org/wiki/File:Roc-draft-xkcd-style.svg

Operating a hydropower system

Floods

- Back to Wallonia. Unforeseen event.
- Climate change was blamed.
  - Why?





Operating a hydropower system

Sediment management

- Sediment can:
  - Damage equipment;
  - Reduce the storage capacity of reservoirs;
  - Cause water quality problems;
  - Lead to morphological and environmental problems downstream.

Operating a hydropower system

Sediment management

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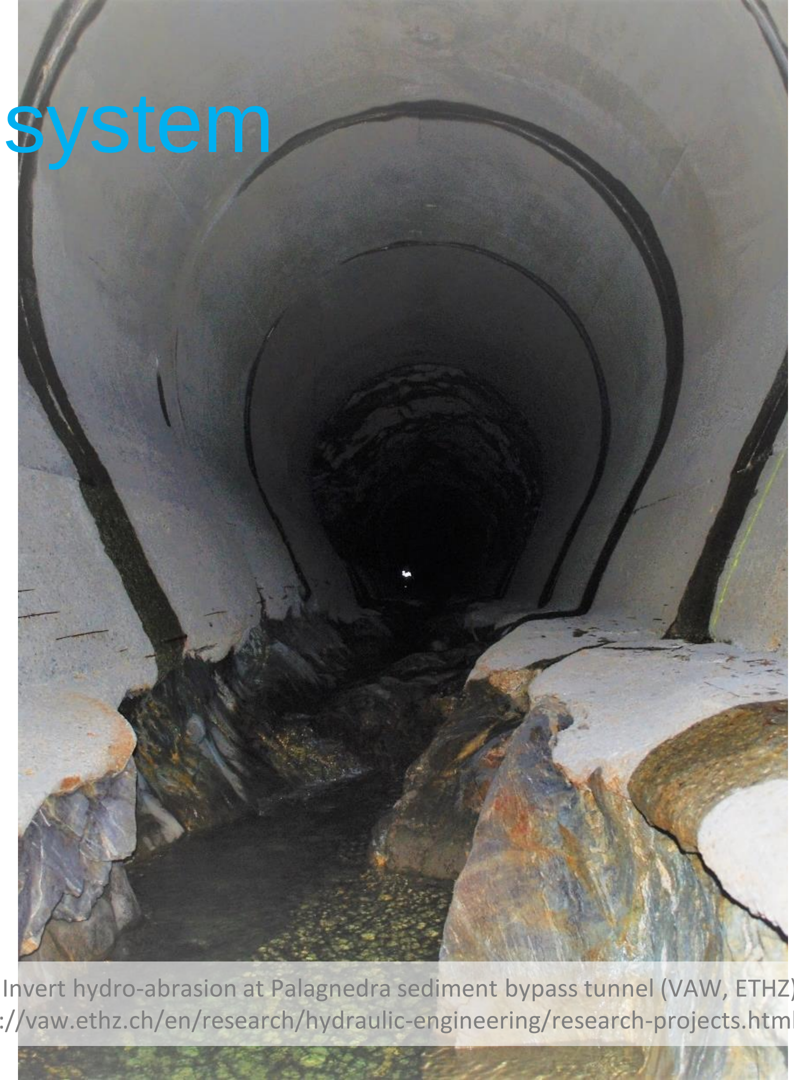
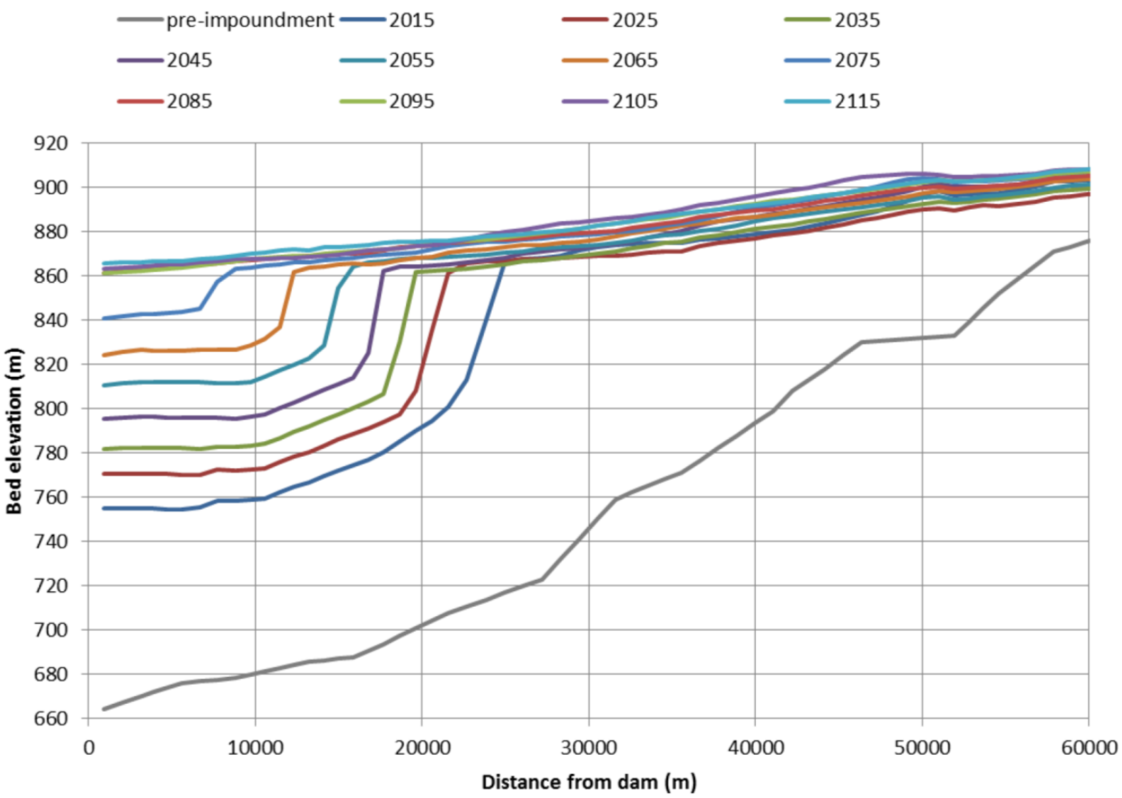


Invert hydro-abrasion at Palagnedra sediment bypass tunnel (VAW, ETHZ)
https://vaw.ethz.ch/en/research/hydraulic-engineering/research-projects.html

Operating a hydropower system

Sediment management

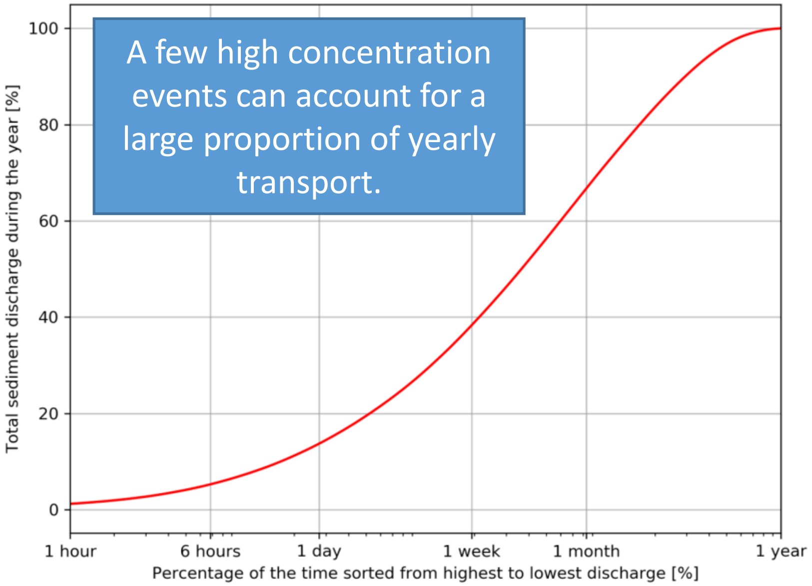
- Reservoirs tend to fill up with sediments over time.
- The issue is particularly problematic in mountainous and/or arid regions.
- Even very large reservoirs can be affected.

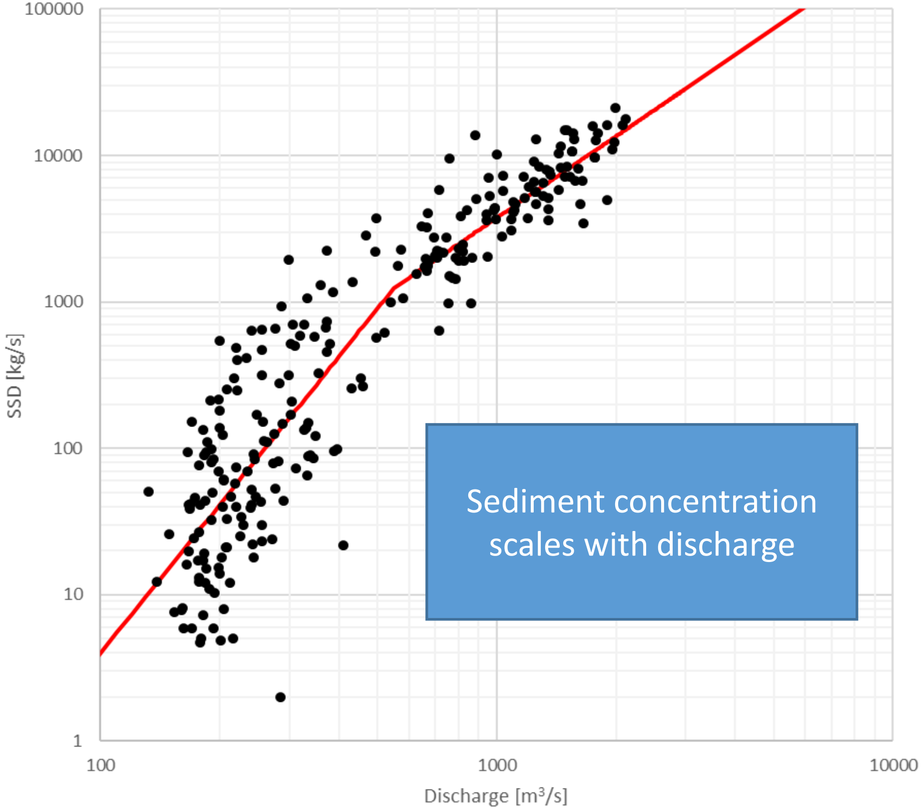


Operating a hydropower system

Sediment management

- Very punctual phenomenon.
- Can be difficult to measure.





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Sediment management

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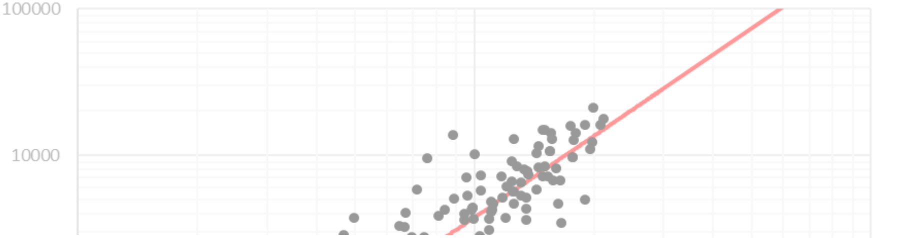

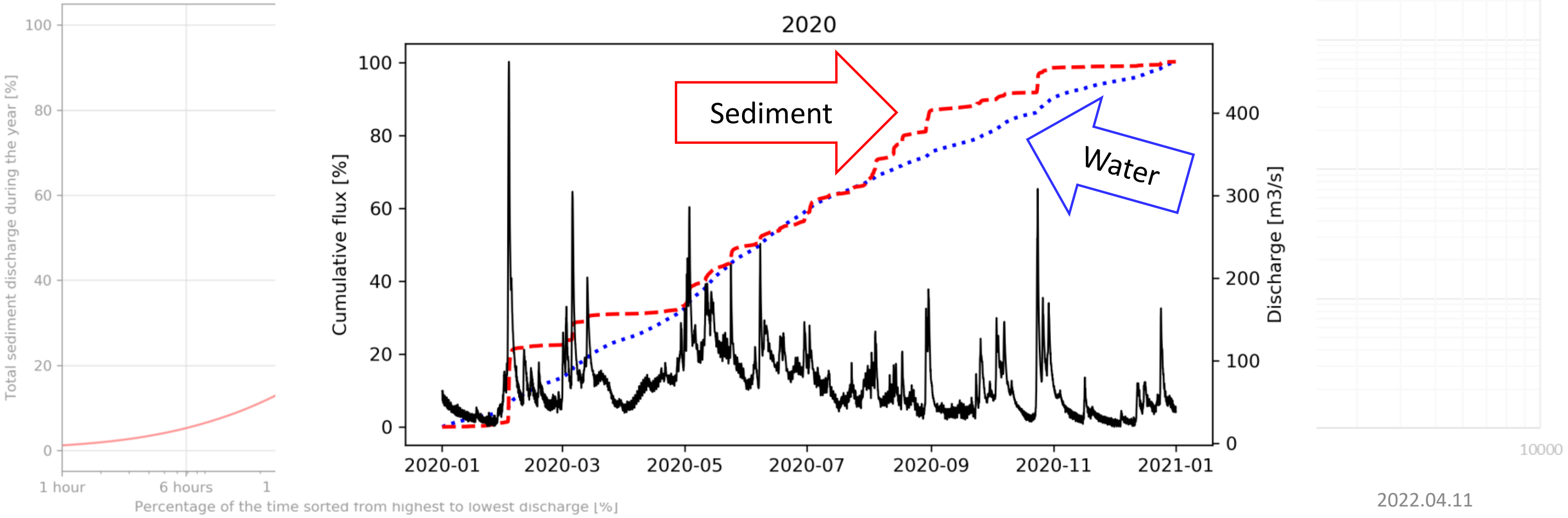

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Environmental flows

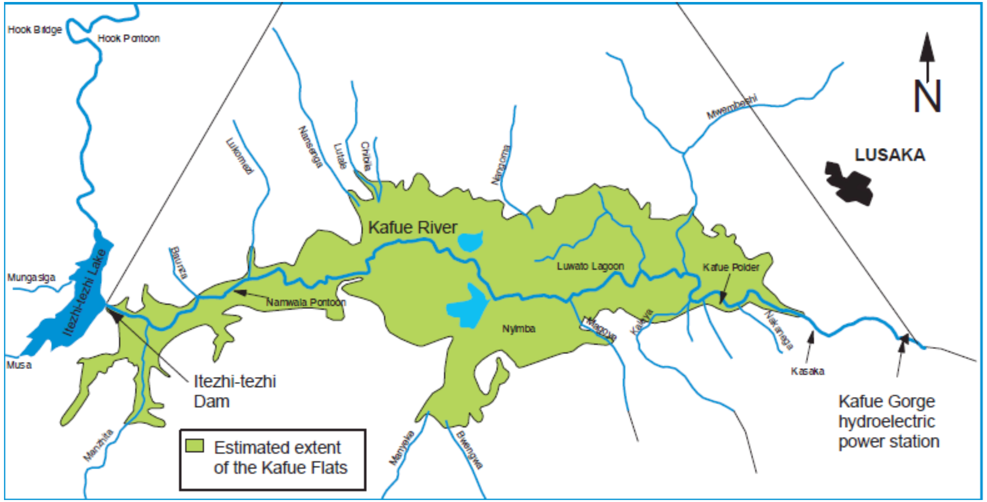
The case of the Kafue Flats, in Zambia

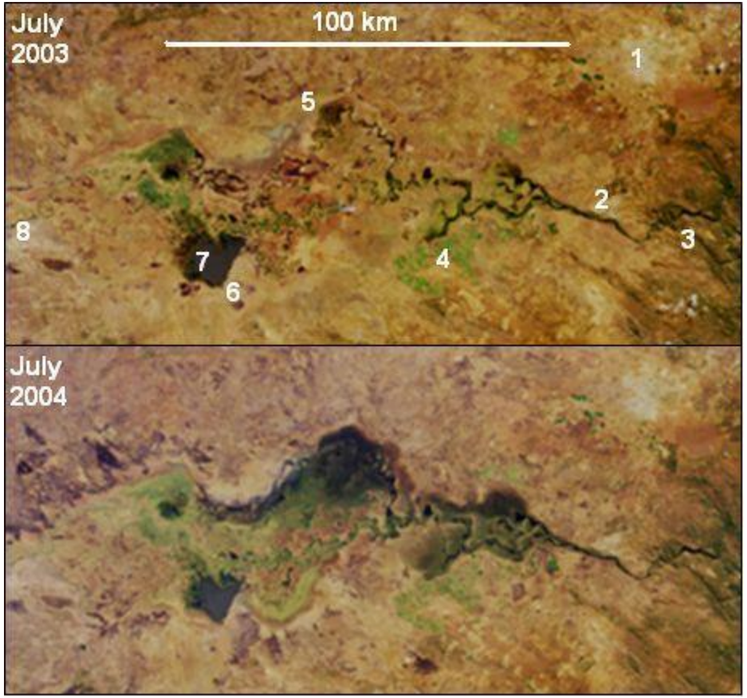

Photo by Wilma Blaser

Environmental flows

The case of the Kafue Flats, Zambia

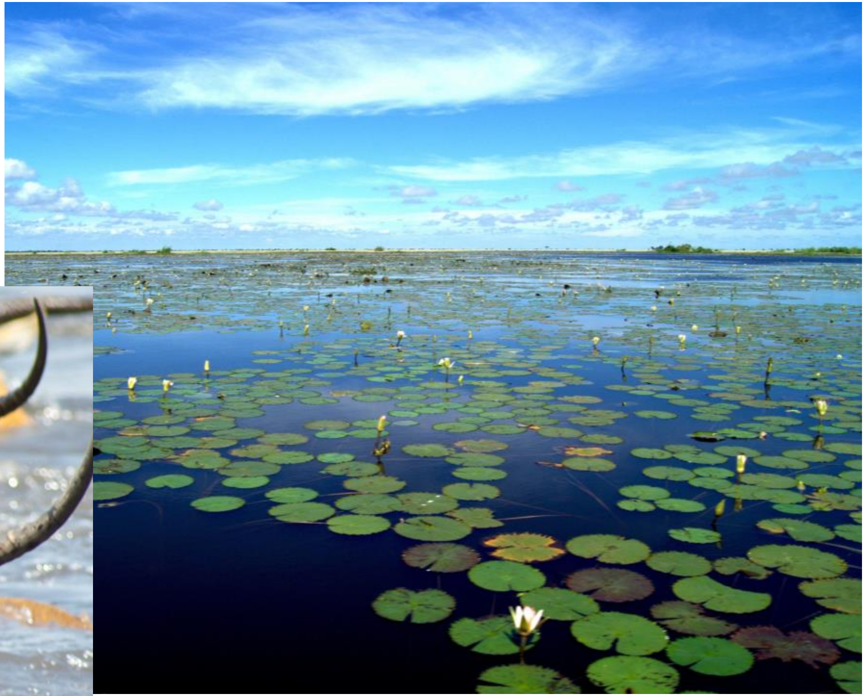
- Not only about quantity but also timing and many other characteristics.

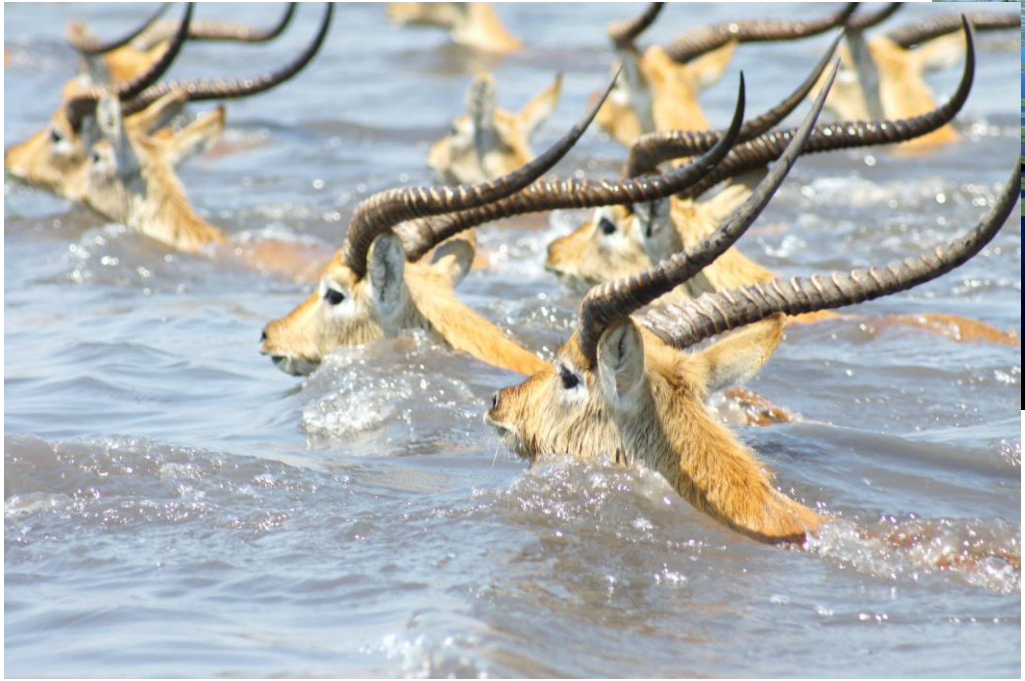




Environmental flows

The case of the Kafue Flats, Zambia





Photos by Wilma Blaser

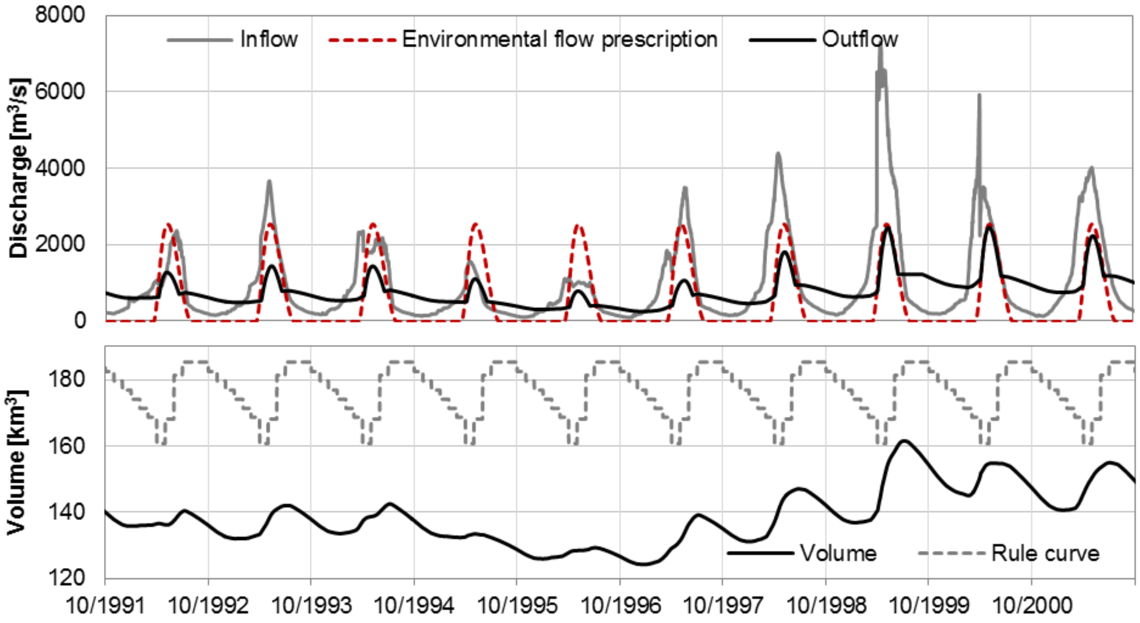
2022.04.11

Environmental flows

The case of the Kafue Flats, Zambia

- Not only about quantity but also timing and many other characteristics.

- Difficult choices must be made.
- Optimization can help.



Climate change

Importance for large hydro
Scenarios and models
Working with the data
So, should I build a dam?

Climate change

Matters a lot for large hydropower

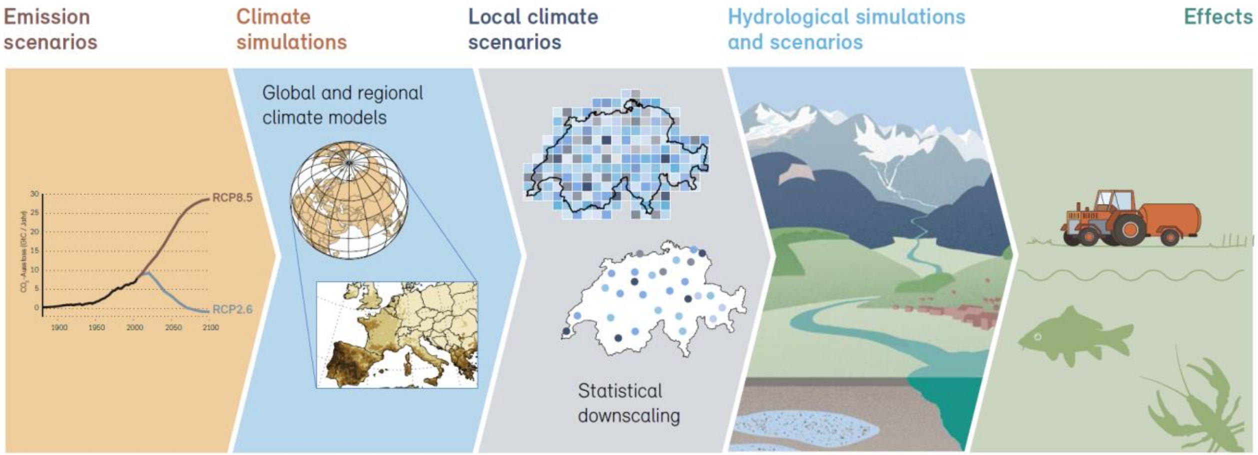
- Enormous potential impacts for large hydro.
  - Evolution of water availability:
    - precipitation, evaporation and glacier retreat.
  - Inter-annual / seasonal variability:
    - Firm energy supply – droughts.
  - Extreme events:
    - Changes in the likelihood of floods and the severity of droughts.

Climate change

Scenarios and models

Figure 2-1: Model chain to assess the effects of climate change on water management

Uncertainties emerge in every process step, starting with the selection of the emission scenarios to be input into the global climate models, then the regionalisation process (improving the resolution) as a pre-requisite for the hydrological modelling, and finally analysis of the effects on water ecology or water management.



Sources of uncertainty

- Development of future greenhouse gas emissions
- Model selection and structure
- Scaling and correction of model results
- Input data

- Initial conditions
- Model parameters
- Data for calibration and validation

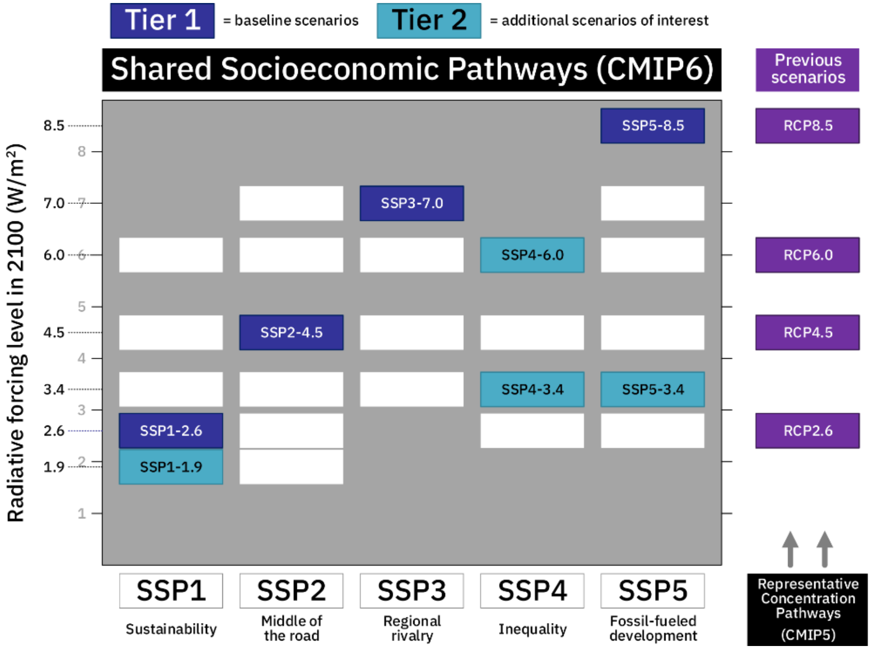
- Natural variability
- Process understanding
- Unforeseeable events which tip the balance of a system

FOEN (ed.) 2021: Effects of climate change on Swiss water bodies. Hydrology, water ecology and water management. FOEN, Bern. Environmental Studies No. 2101
https://www.nccs.admin.ch/nccs/fr/home/changement-climatique-et-impacts/schweizer-hydroszenarien.html

Climate change

Scenarios and models

- Shared Socioeconomic Pathways (SSPs) with
- future climate radiative forcing (RF) outcomes (RCPs)

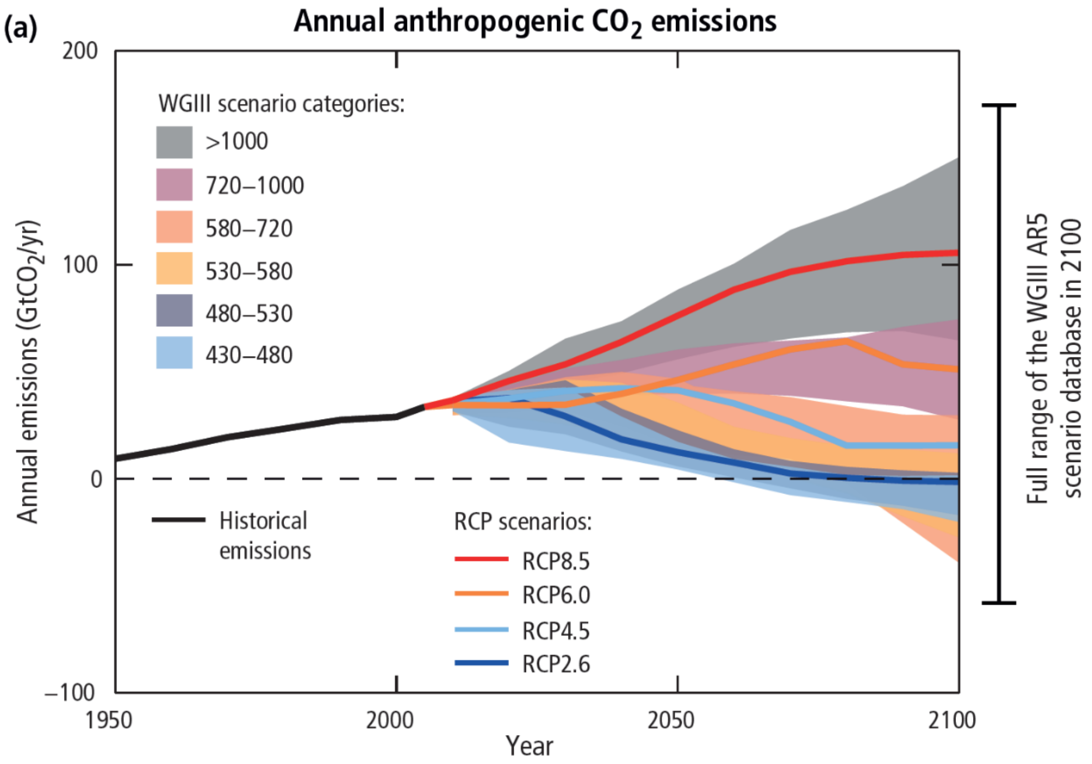


Matthew J. Gidden et al., Global emissions pathways under different socioeconomic scenarios for use in CMIP6: a dataset of harmonized emissions trajectories through the end of the century, Geosci. Model Dev., 12, 1443–1475, 2019, https://doi.org/10.5194/gmd-12-1443-2019
https://en.wikipedia.org/wiki/Coupled_Model_Intercomparison_Project#/media/File:SSPs-CMIP6.svg

Climate change

Scenarios and models

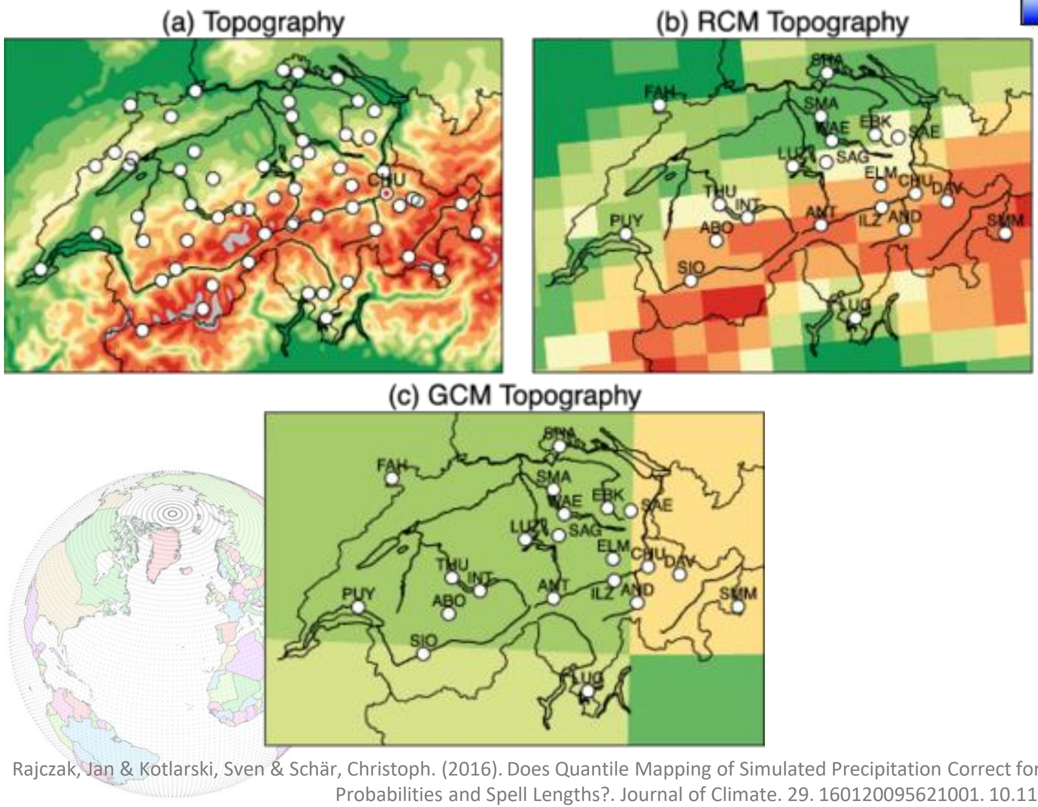
- Shared Socioeconomic Pathways (SSPs) with
- future climate radiative forcing (RF) outcomes (RCPs)

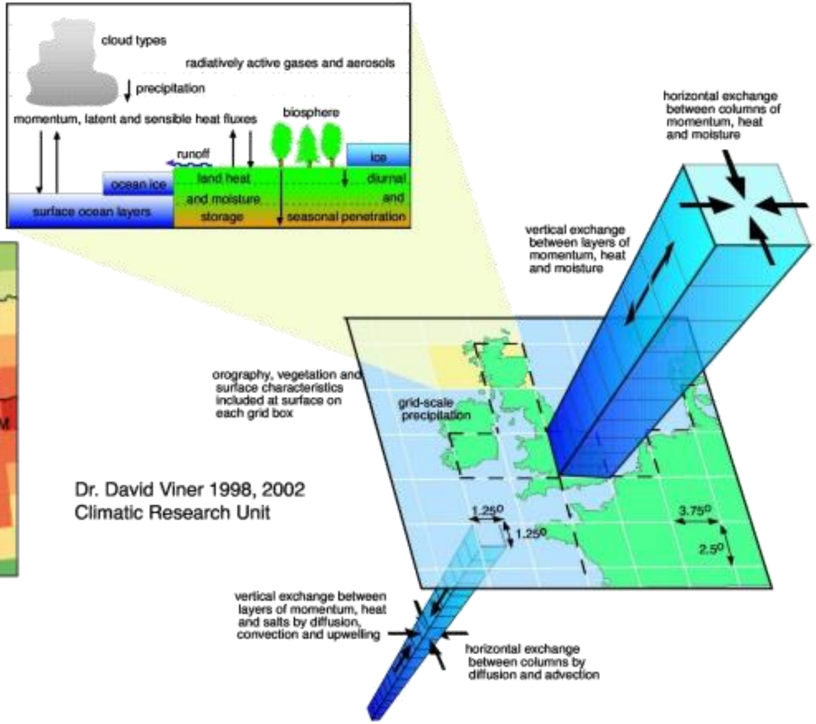


IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Climate change

Scenarios and models



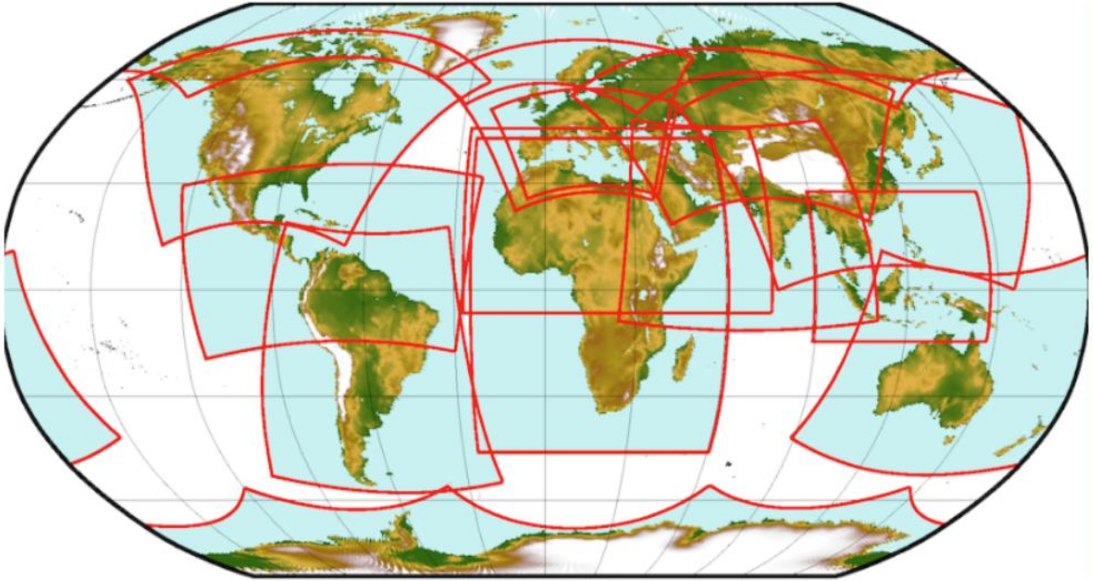


Rajczak, Jan & Kotlarski, Sven & Schär, Christoph. (2016). Does Quantile Mapping of Simulated Precipitation Correct for Biases in Transition Probabilities and Spell Lengths?. Journal of Climate. 29. 160120095621001. 10.1175/JCLI-D-15-0162.1

https://www.wcrp-climate.org/wgcm-cmip/cmip-video
https://www.ipcc-data.org/guidelines/pages/gcm_guide.html

Climate change

Scenarios and models

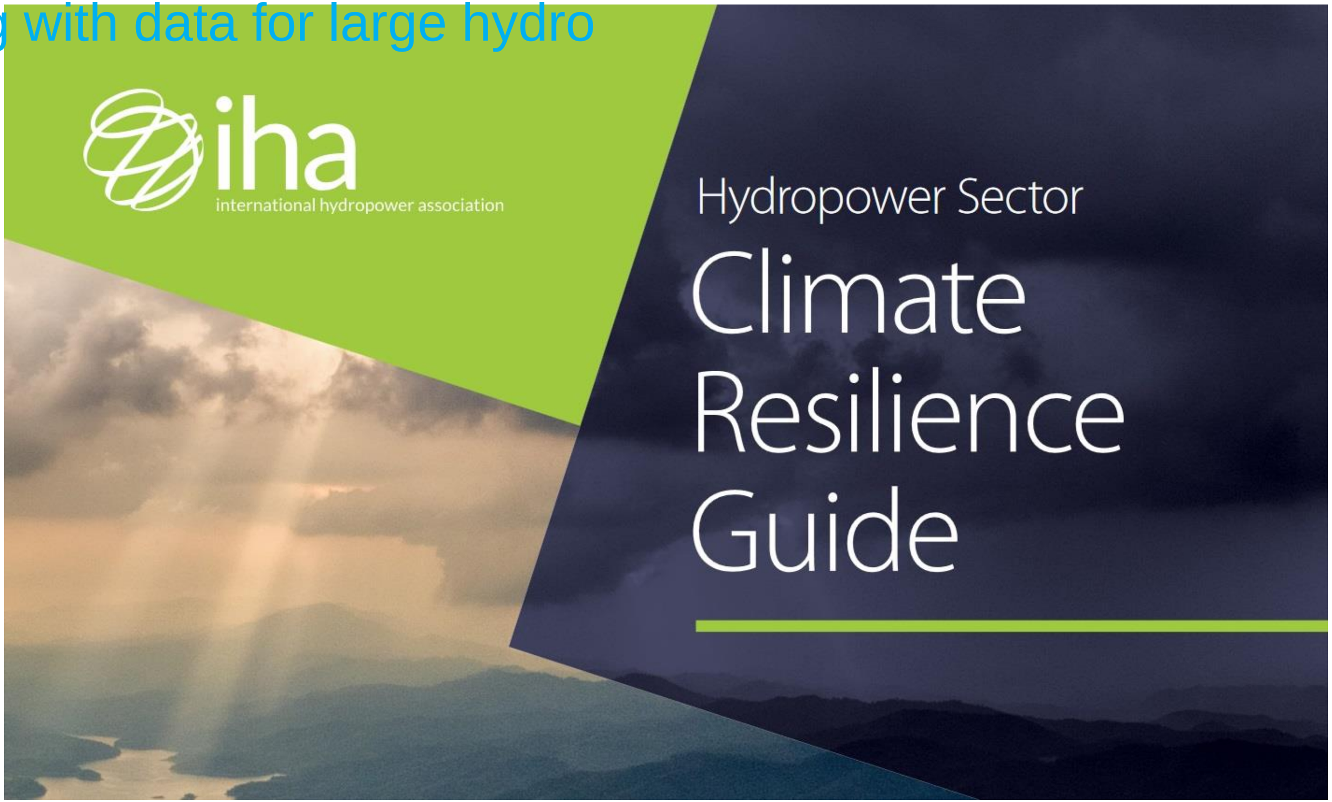


- Region 1: South America
- Region 2: Central America
- Region 3: North America
- Region 4: Africa
- Region 5: Europe (EURO)
- Region 6: South Asia
- Region 7: East Asia
- Region 8: Central Asia
- Region 9: Australasia
- Region 10: Antarctica
- Region 11: Arctic
- Region 12: Mediterranean (MED)
- Region 13: Middle East North Africa (MENA)
- Region 14: South-East Asia (SEA)

https://cordex.org/

Climate change

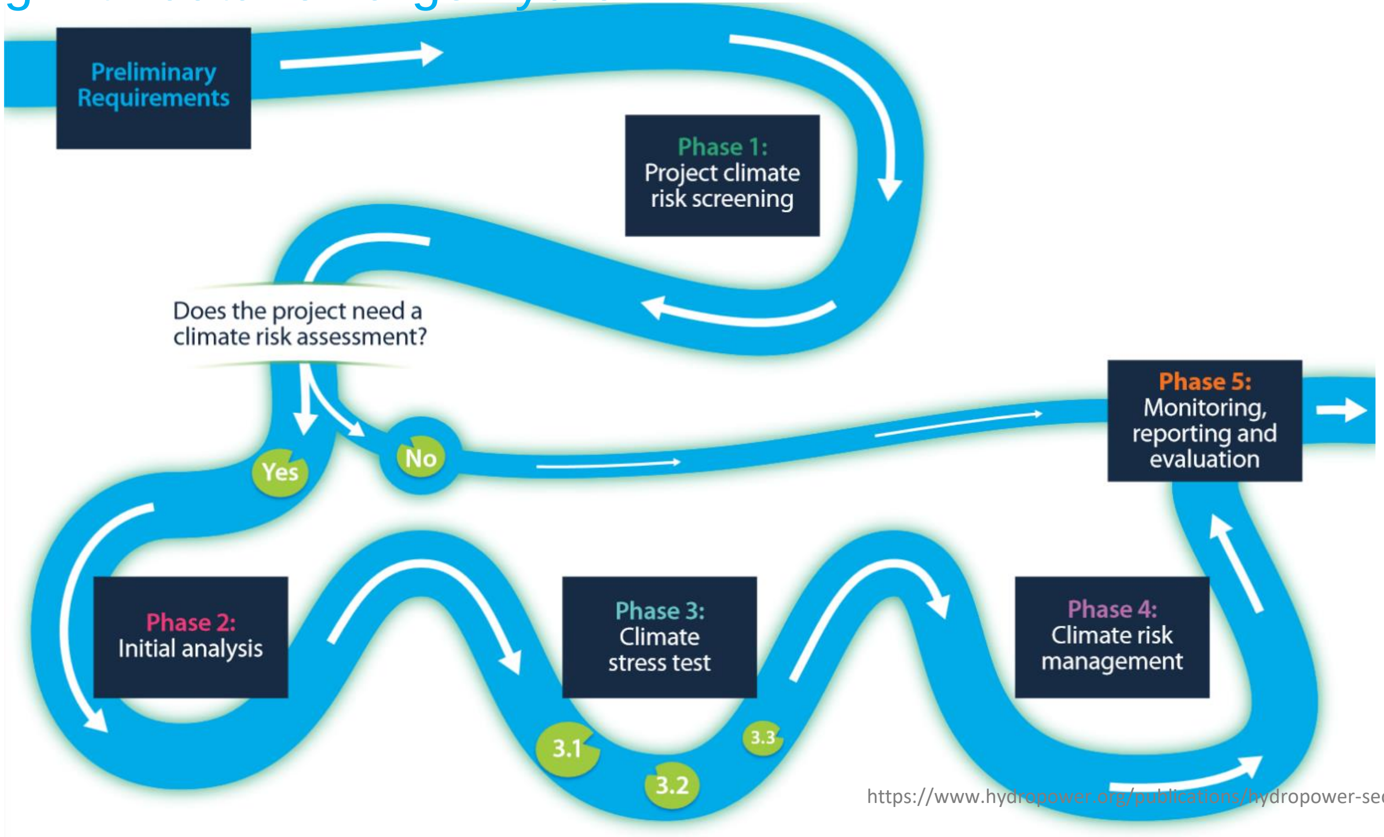
Working with data for large hydro



https://www.hydropower.org/publications/hydropower-sector-climate-resilience-guide

Climate change

Working with data for large hydro

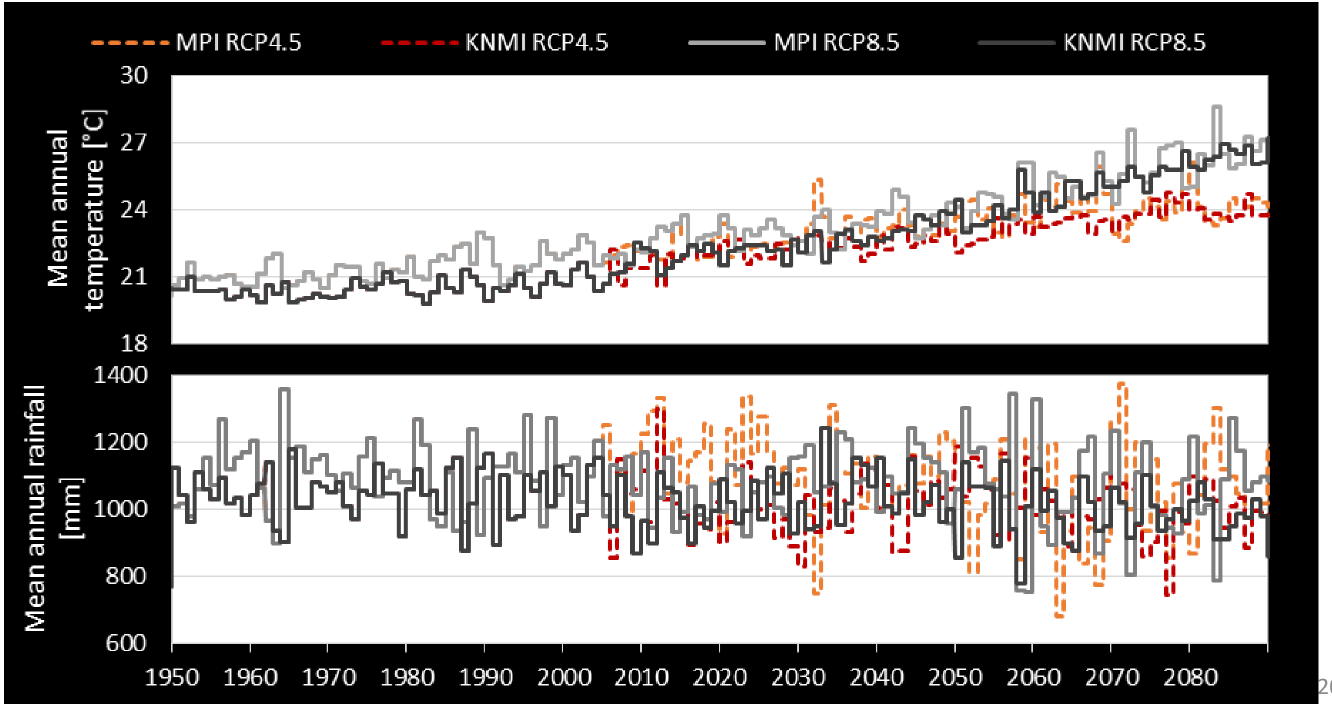


https://www.hydropower.org/publications/hydropower-sector-climate-resilience-guide

Climate change

Working with data for large hydro

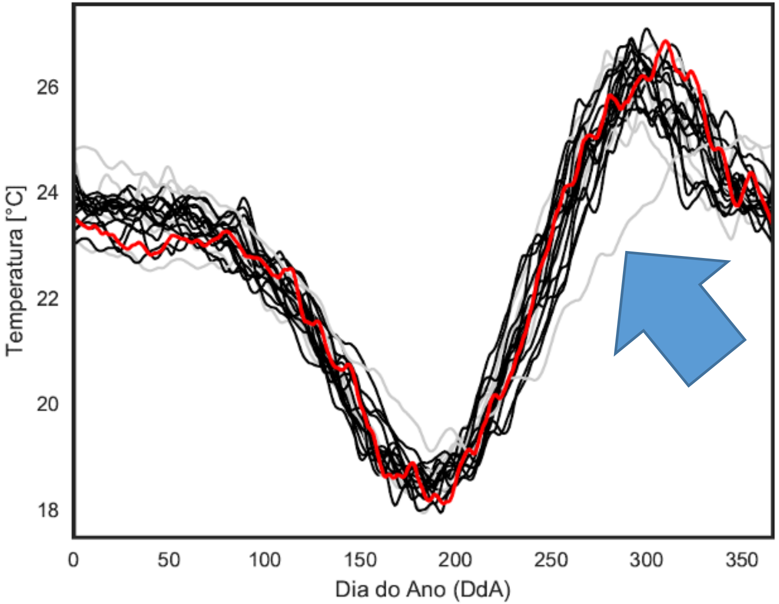
- Climate projections ≠ forecasts

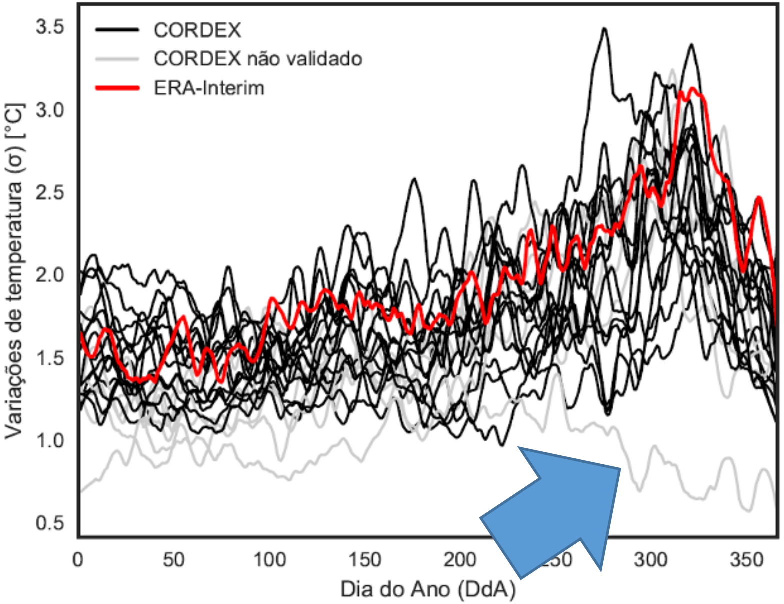


Climate change

Working with data for large hydro

- A reference is required for the historical period:
  - Ground data, gridded observations, or reanalysis.
- Correction of average values, seasonal distribution and variability.

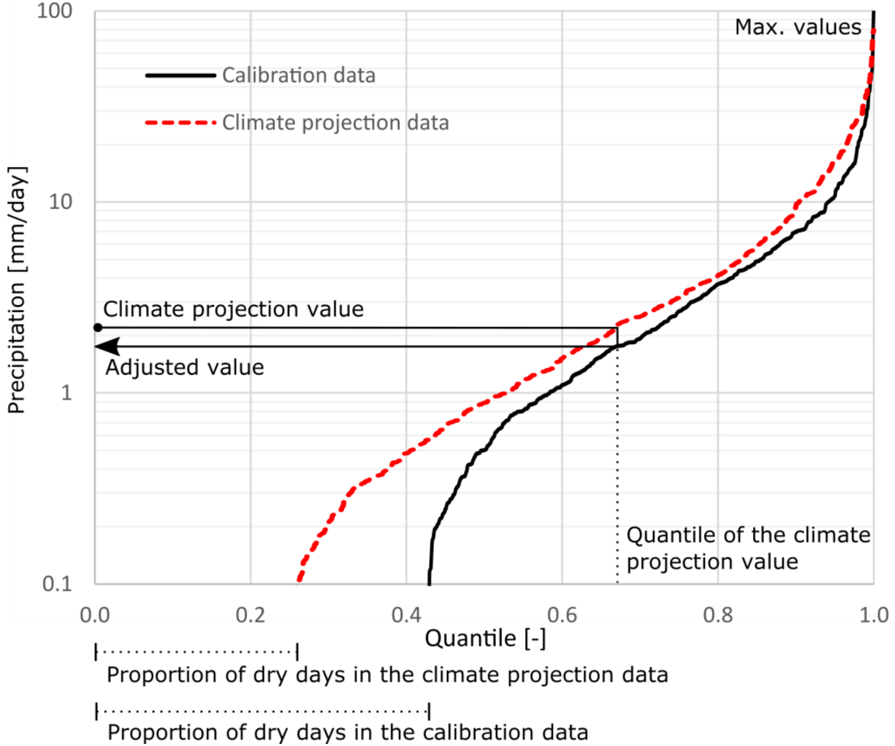




Climate change

Working with data for large hydro

- How to match projections and the reference?
  - Different challenges for precipitation and temperature.
- Precipitation:
  - Quantile mapping.
  - Problem when there are more dry days in the projections.
- Temperature:
  - Quantile mapping or linear transformation.
  - For QM: problem regarding future extremes.

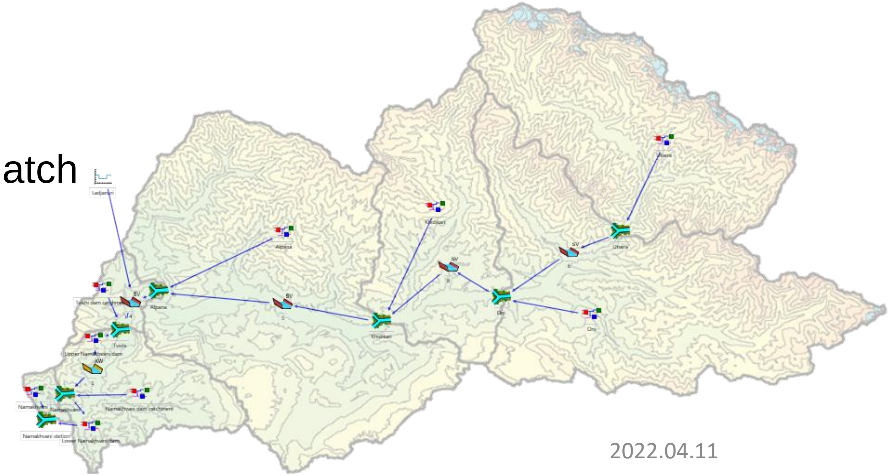


Climate change

So, should I build a dam?

- After validation we have a fair number of projections for the chosen scenarios.
  - Temperature, Precipitation…
- To get discharges we need:
  - A hydrologic model.
  - Input data.
  - Calibration data.

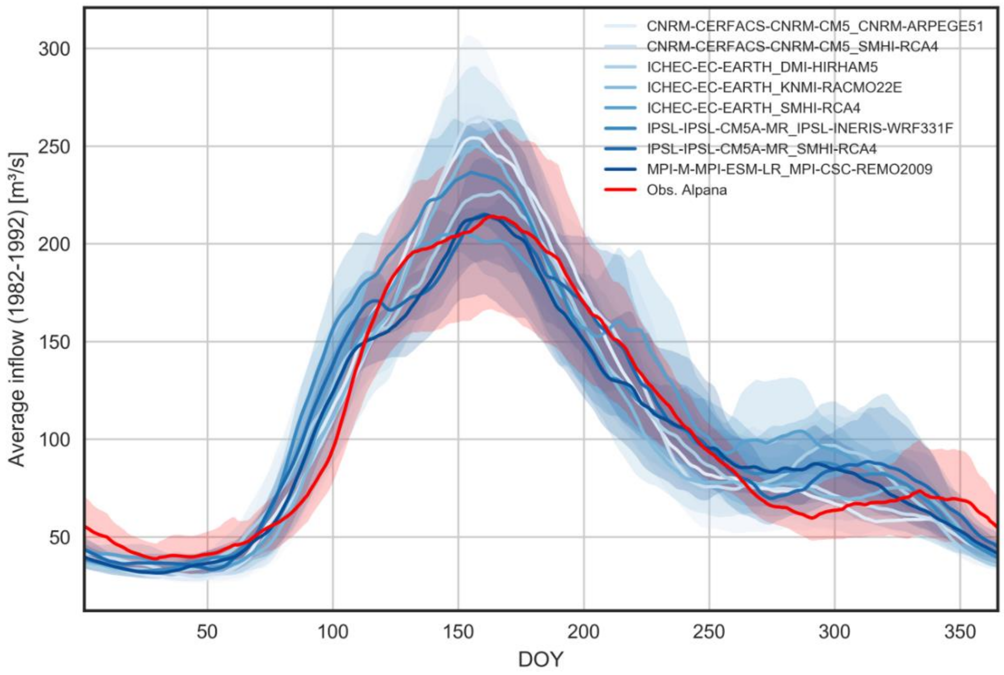
  - Problem: calibration discharges do not match historical projections.
  - The model is:
    - Calibrated with observations
    - But run with projections
    - They must agree!



Climate change

So, should I build a dam?

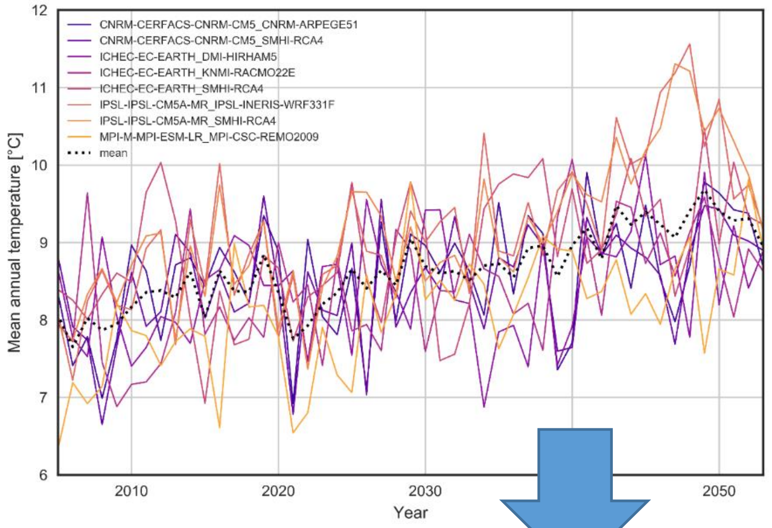
- Second verification required after the hydrology is simulated.
  - Average values, seasonal distribution and variability.

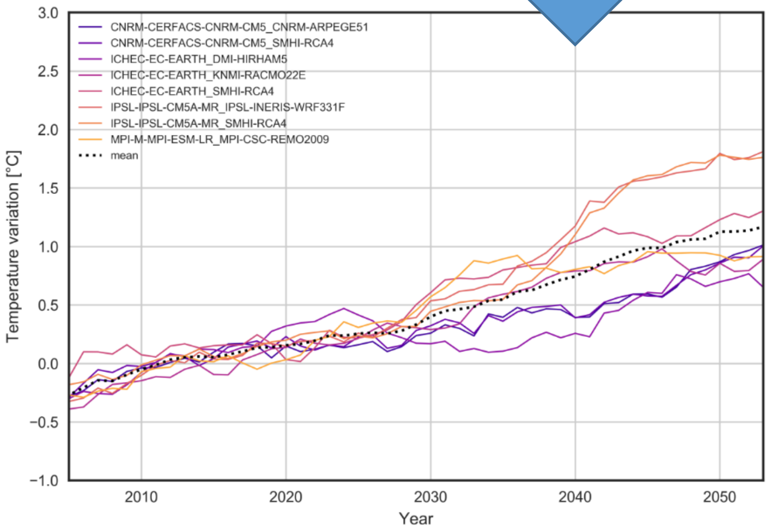


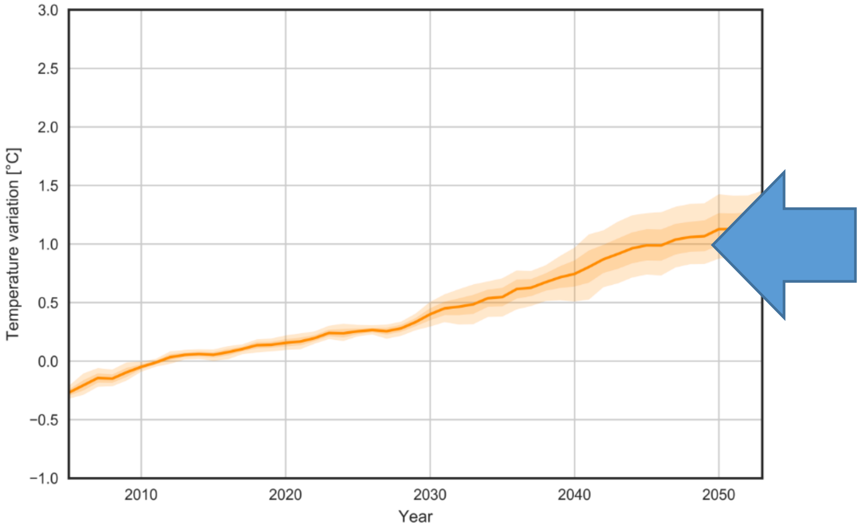
Climate change

So, should I build a dam?

- Smooth data and results…
- Average different models for uncertainty.
- Do not focus on specific years.



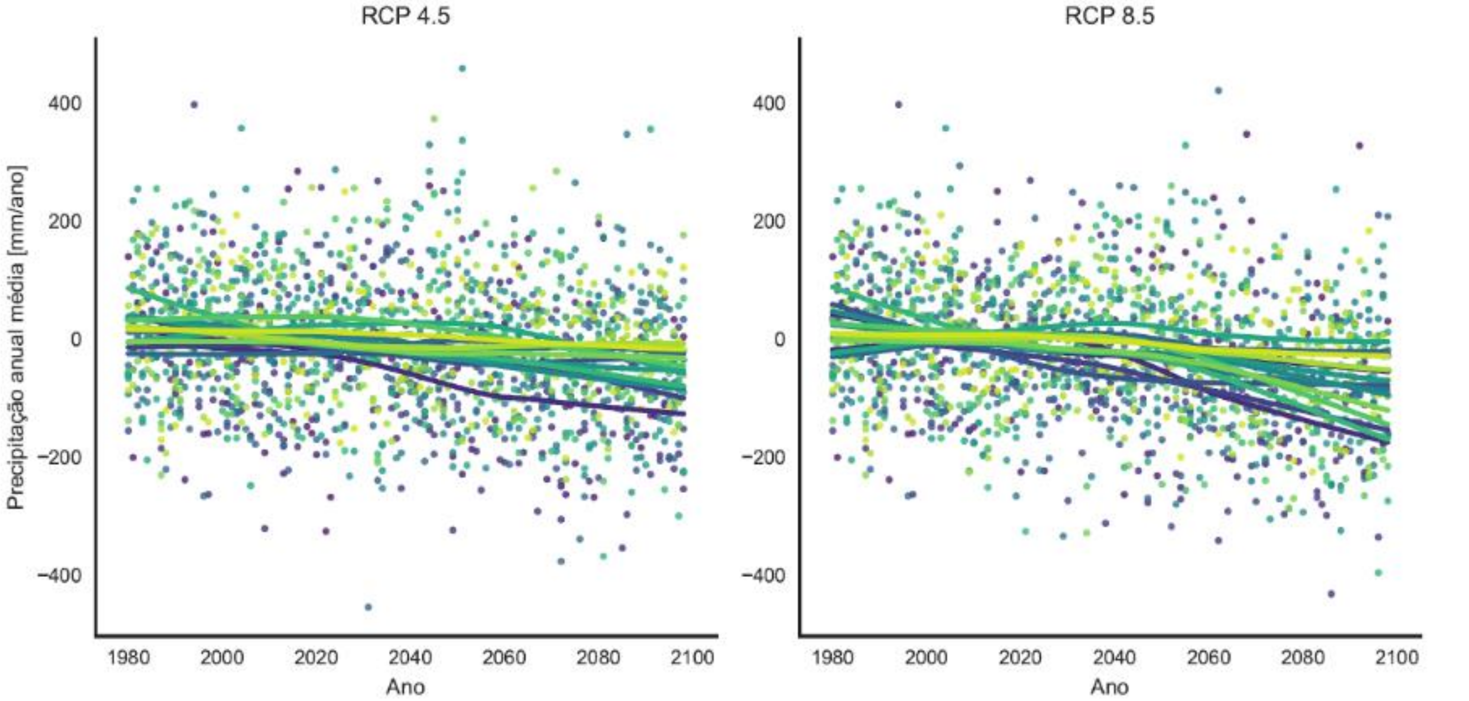




Climate change

So, should I build a dam?

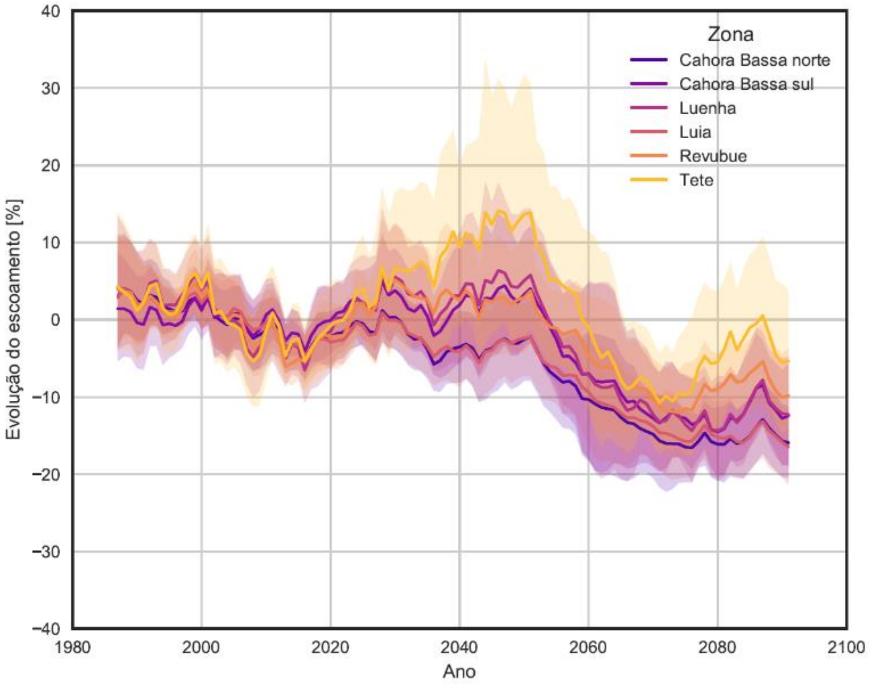
- “Clean” results often mask a huge uncertainty.

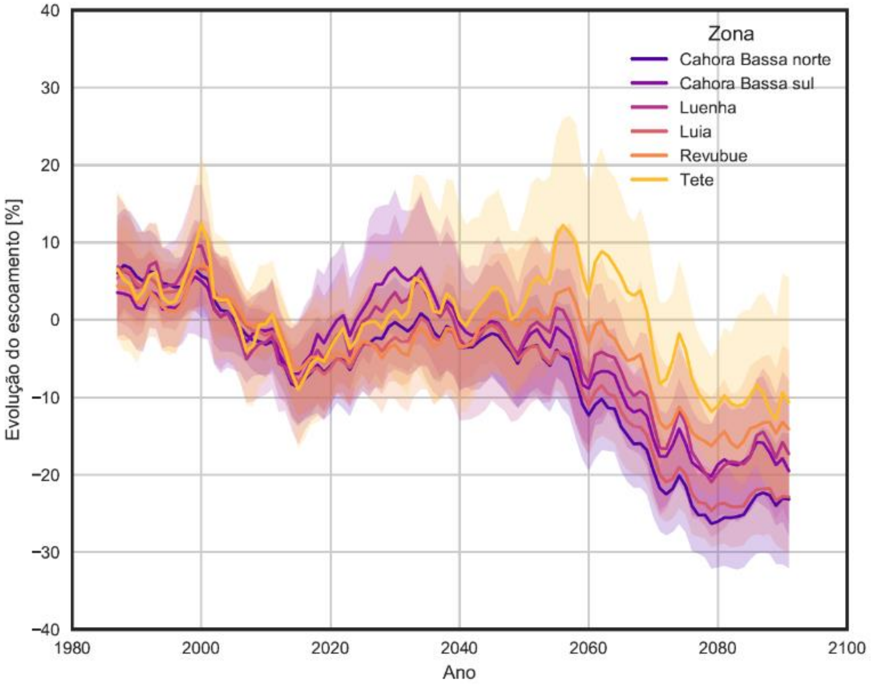


Climate change

Once too skeptical, now a realist

- Example of discharge trends in Southern Africa.





Risk of failure

What about risk?

Black swans and dragon kings

Consequences for large dams

It take courage to act

Risk of failure

What about risk?

What is risk?

Risk = Probability of occurrence x Loss

Often, one or both aspects are not correctly defined when risk is "quantified".

$$R = (A, C, U, P, K)$$

where:

A is an event that might occur

C is the consequences of the event

U is an assessment of uncertainties

P is a knowledge-based probability of the event

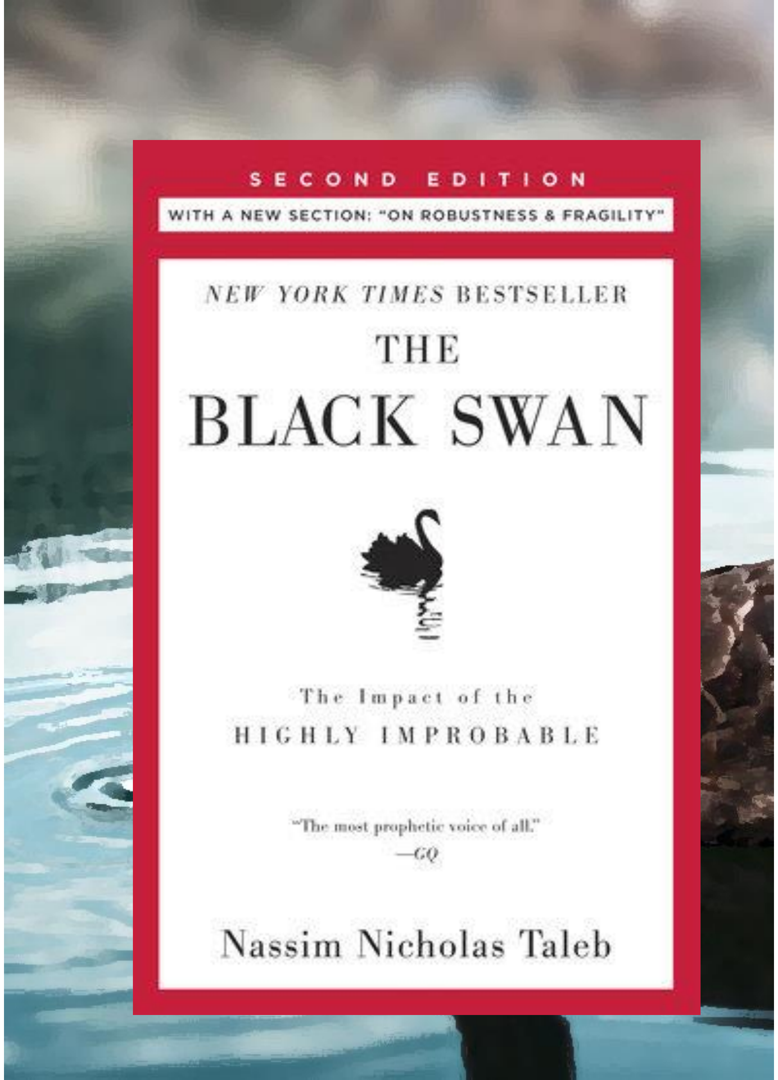
K is the background knowledge that U and P are based on

https://en.wikipedia.org/wiki/Risk

Risk of failure

Of black swans and dragon kings

- Black Swans
  - an event that comes as a surprise, has a major effect, and is often inappropriately rationalized after the fact with the benefit of hindsight.
  - some events cannot be predicted…
- and Dragon Kings
  - an event that is both extremely large in size or impact (a "king") and born of unique origins (a "dragon") relative to its peers (other events from the same system).
  - are generated by or correspond to mechanisms (…) that tend to occur in nonlinear and complex systems, and serve to amplify DK events to extreme levels



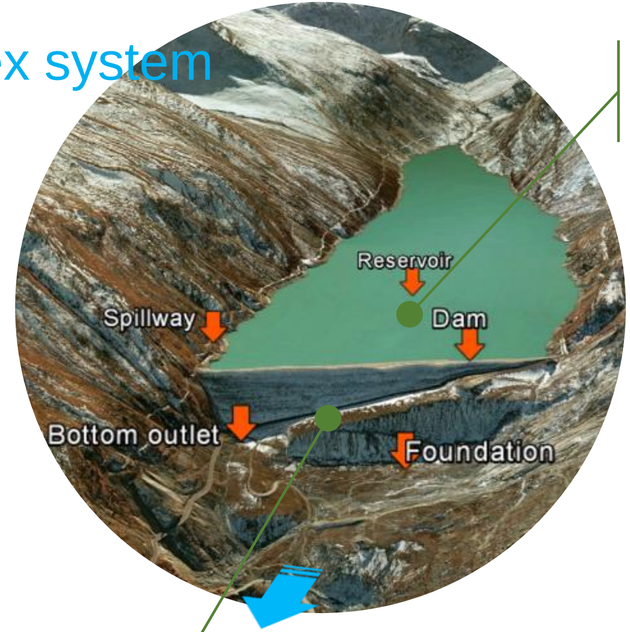
Risk of failure

Dams are dangerous

- The cases of Banqiao and Vajont

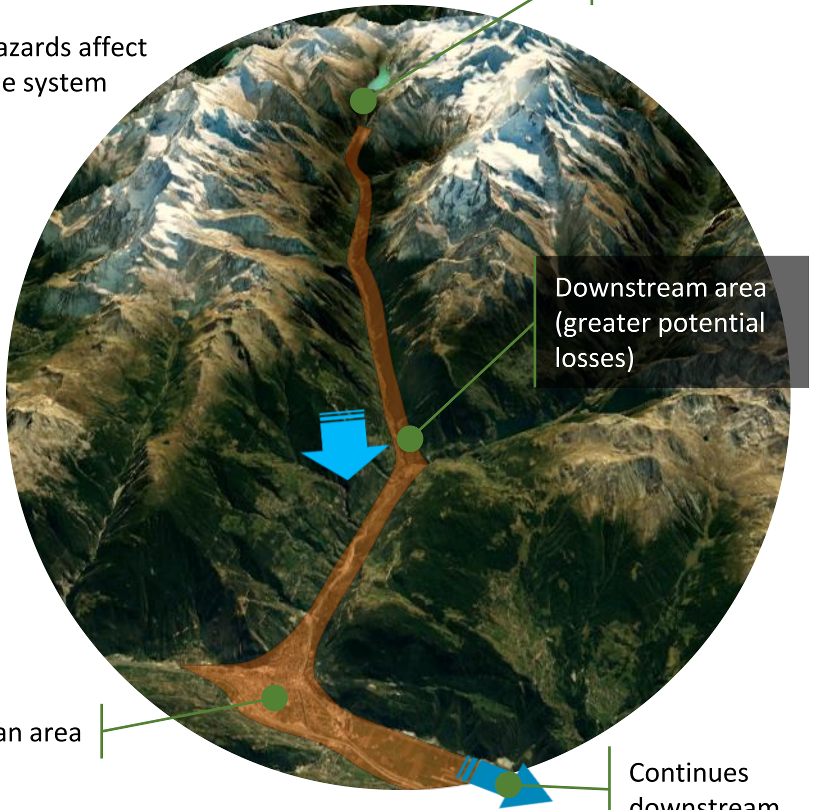
Risk of failure

A complex system



Hazards affect the system

Example: earthfill dam.



Dam

Downstream area (greater potential losses)

Urban area

Continues downstream

Risk of failure

Floods and geology

Failures of dams > 15 m high outside China

Number of:	Masonry gravity dams	Concrete gravity dams	Arch dams	Buttress + multiple arch dams	Fill dams > 30 m	Fill dams < 30 m	Reservoirs	Gates	Total failures	Lives lost
Dams	700	3000	1000	500	3000	9000	17,200			
Failures	18	7	4	9	42	117	2	5	204	
Floods during construction					16	5			21	1300
Flood during operation	7	1	1		12	47			68	7300
Upstream dam-break waves	2				1	3			6	1000
Earthquakes					1	2			3	
War	2	2			2				6	1300
First filling	6	3	3	7	5	24	2	2	52	5500
Ageing (inc piping)	1	1		2	5	26		3	38	600
Unclassified						10			10	
Total lives lost	4200	600	400	800	1500	6700	2700	100		17,000

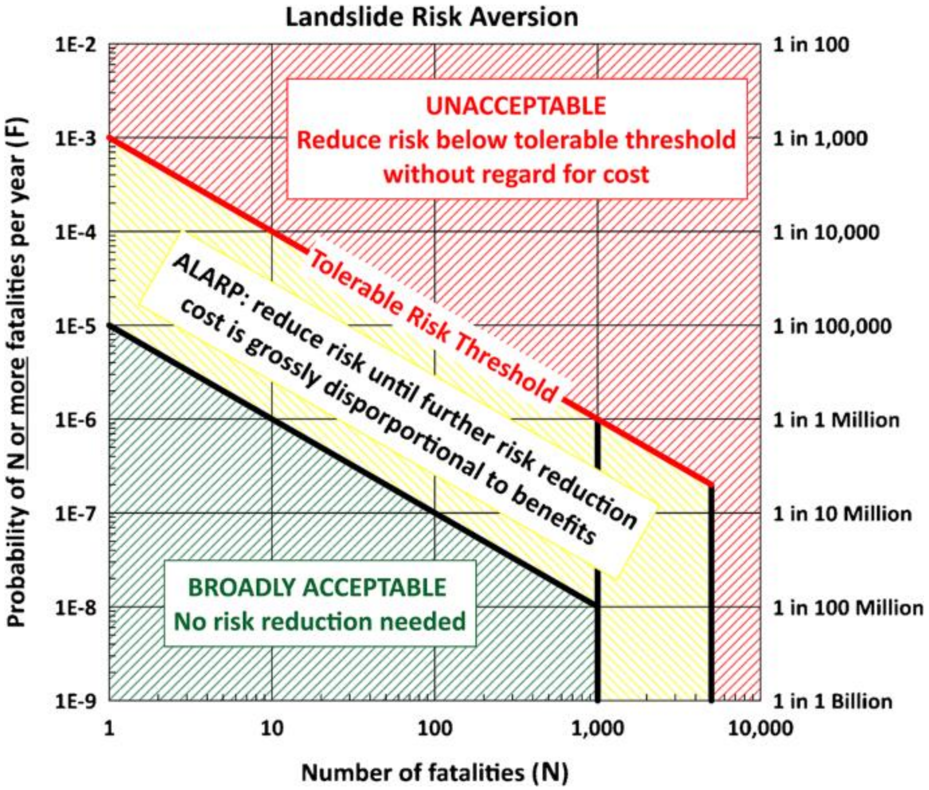
Lempérière, F., 1999. Risk analysis: what sort should be applied to and to which dams?. Hydropower & Dams.

Risk of failure

Acceptance

- ALARP concept:
  - As low as reasonably practicable.

- Profound philosophical and political implications.
- Not accepted in every country.
- "de facto" standard.



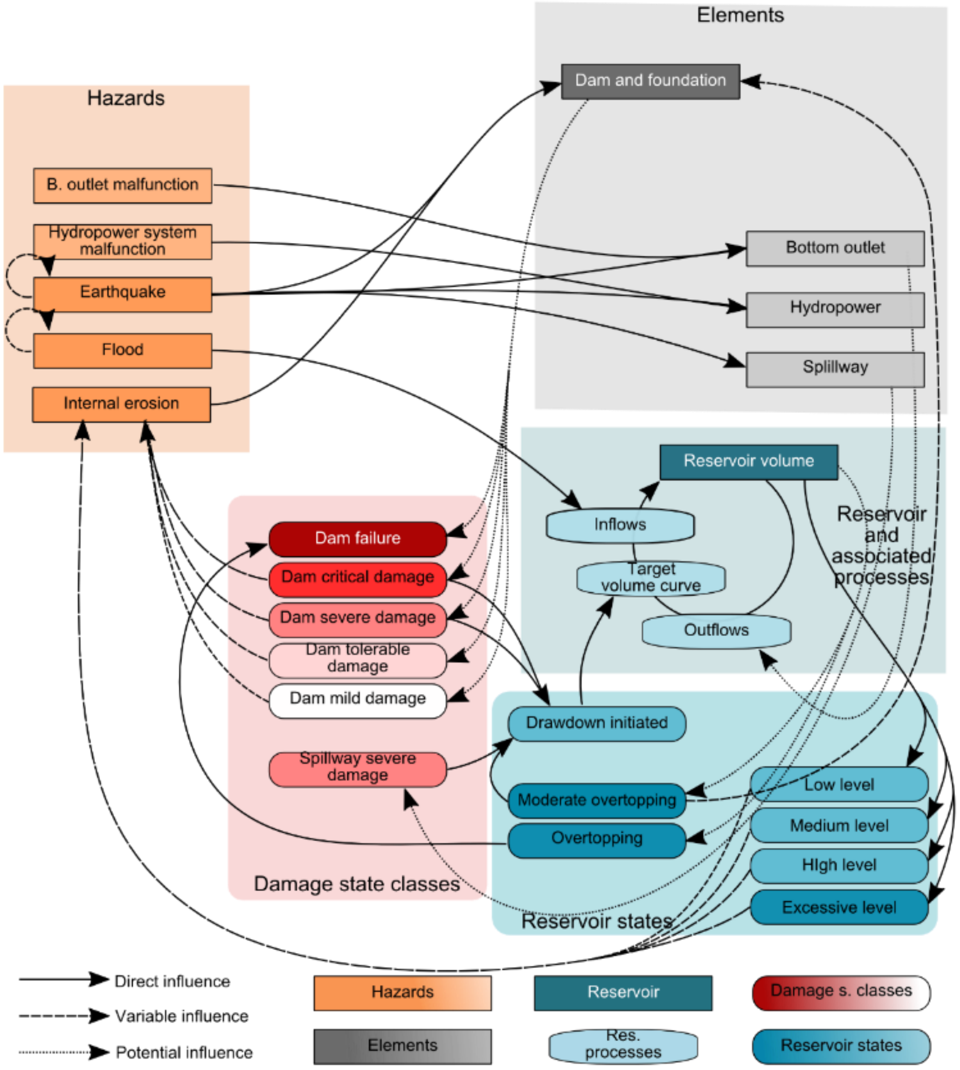
Strouth, A. And McDougall, Landslides. 2020.
https://link.springer.com/article/10.1007/s10346-020-01547-8

Risk of failure

Difficult to estimate

- (Very) simplified representation of a dam-reservoir system.

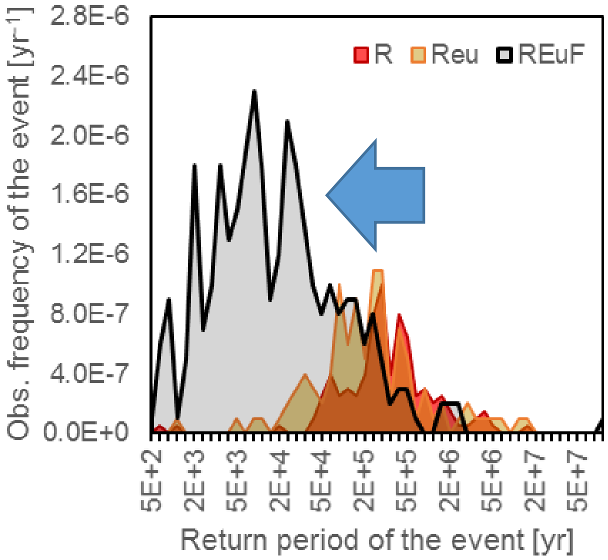
- Inter-actions.
- Intra-actions.
- Coincidences.

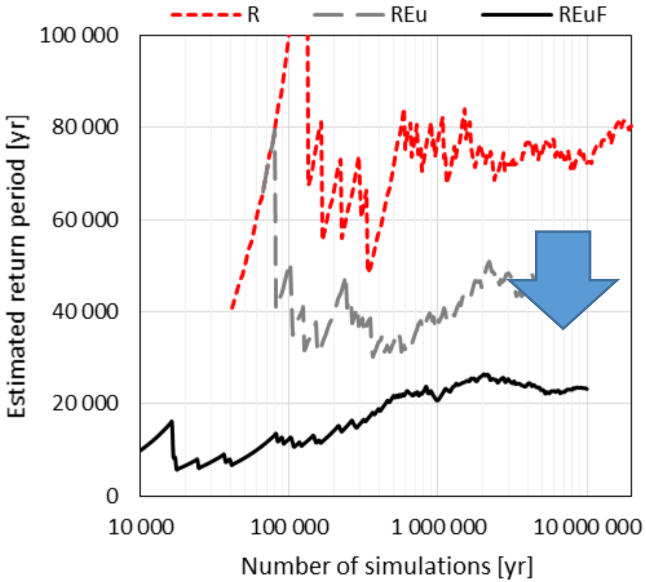


Risk of failure

Difficult to estimate

- The effect of epistemic uncertainty and fragility on risk for a dam.





(R) reference case

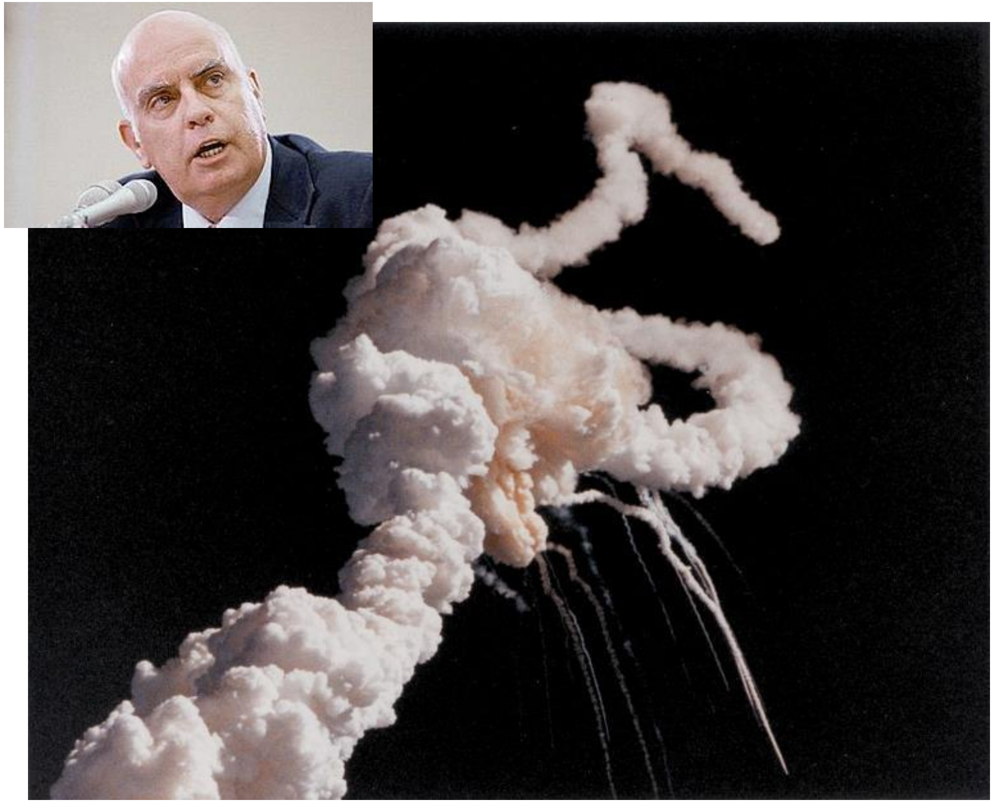
(REu) epistemic uncertainty

(REuF) epistemic uncertainty and fragility

Risk of failure

It takes courage to act

- On how decisions are made.
    - Low-probability high-consequence events are hard to address.
    - Professionalism vs. personal interest (not corruption).
    - Roger Boisjoly and the o-rings that led to the disaster of the Challenger Space Shuttle (1986).



https://commons.wikimedia.org/wiki/File:Challenger_explosion.jpg

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SWARM

Co-funded by the Erasmus+ Programme of the European Union

Strengthening of master curricula in water resources management for the Western Balkans HEIs and stakeholders

Practical challenges of large hydropower

Thank you

Online quiz 14-16

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