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# Hydrological systems


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In cooperation with the CTI

Energy
Swiss Competence Centers for Energy Research

Schweizerische Eidgenossenschaft
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# Objective

- ***Why understanding hydrological systems is important***
- ***What we need to understand about hydrology***
- ***What is needed to understand the interplay of hydrological systems and hydropower operation***

# Why understanding hydrological systems is important

- Hydropower (HP) operation and production depends on water availability, i.e. streamflow regime
  - *A better knowledge of hydrology allows to increase the reliability of design and operation*
- Streamflow regimes depend in turn on climate forcing and river basin response
  - *A better knowledge of basin response dependence on climate variability helps anticipating the impacts of severe operating conditions*
- The management of reservoirs and related infrastructure depends on processes that are driven by hydrology
  - *A better knowledge of hydrology driven processes (e.g. sediment production and transport upstream of reservoirs) helps anticipating the impact of limiting conditions to hydropower systems operation*
- The safety of dams and hydropower infrastructure depends on their ability to withstand extreme events
  - *A better knowledge of hydrologic extremes allows a reliable design of safety organs of dams (e.g. spillway)*

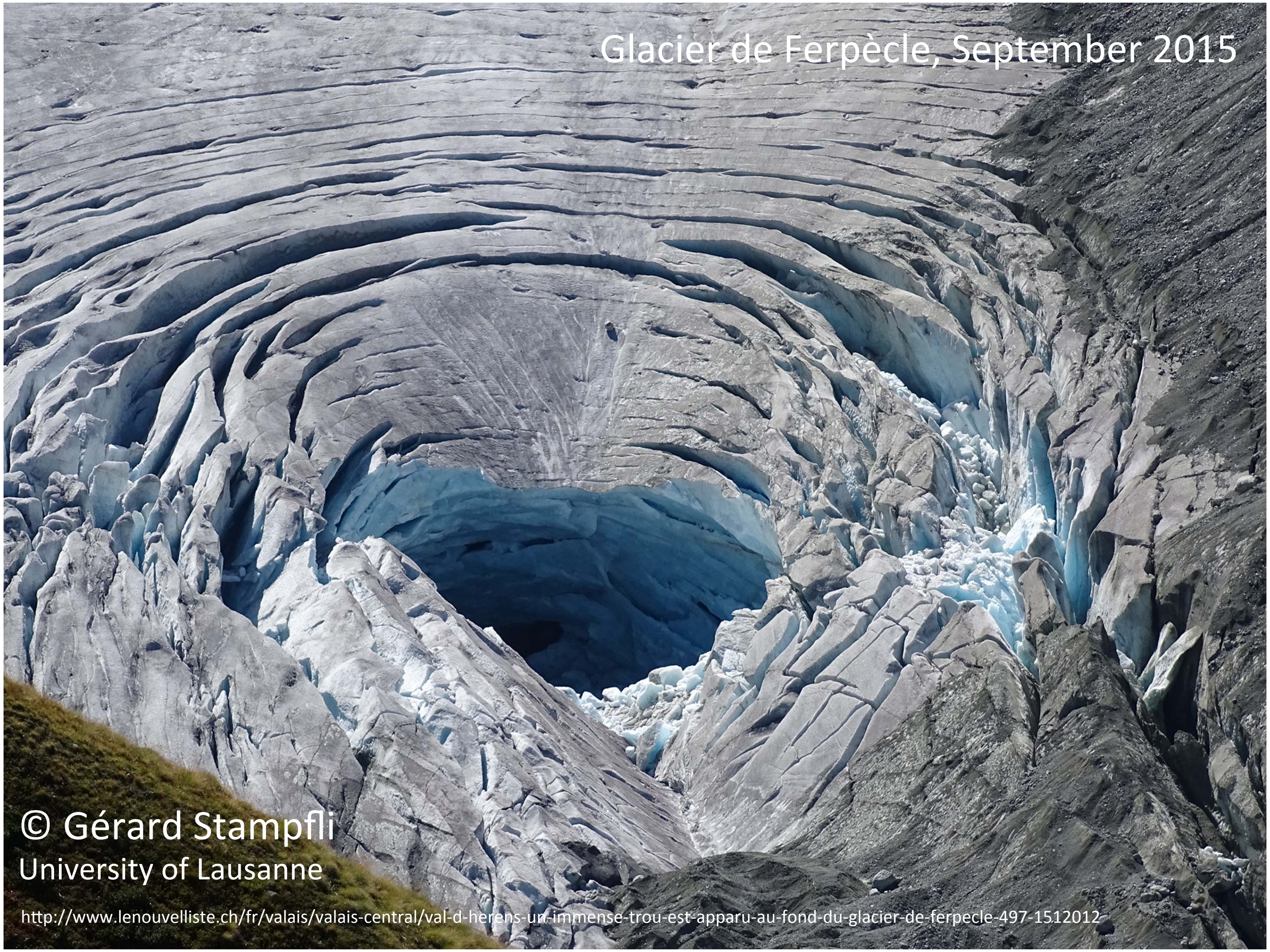
# What we need to understand about hydrology

- Variability of hydrologic response across a range of spatial and temporal scales
  - *e.g. hourly scale for extreme events and for hydropower operation in response to market*
  - *e.g. **spatially explicit** (distributed) description of the basin response to account for local conditions*
- Long-term behaviour of hydrologic systems
  - *to increase the representativeness of prediction of the system response and to quantify the **uncertainty** associated to it*
- Extreme events
  - *high return period peak flows and associated duration and volume*
- Changing basin characteristics
  - *glacier mass-balance variability*
- Impact of streamflow regulation on river corridors due to HP operation
  - *spatially explicit description of the propagation of effects along the river corridor*

**☞ physically based models to simulate the basins response ☜**

**☞ stochastic framework ☜**

# … speaking of basin changes…



# HP and hydrology under changing climate (new questions)

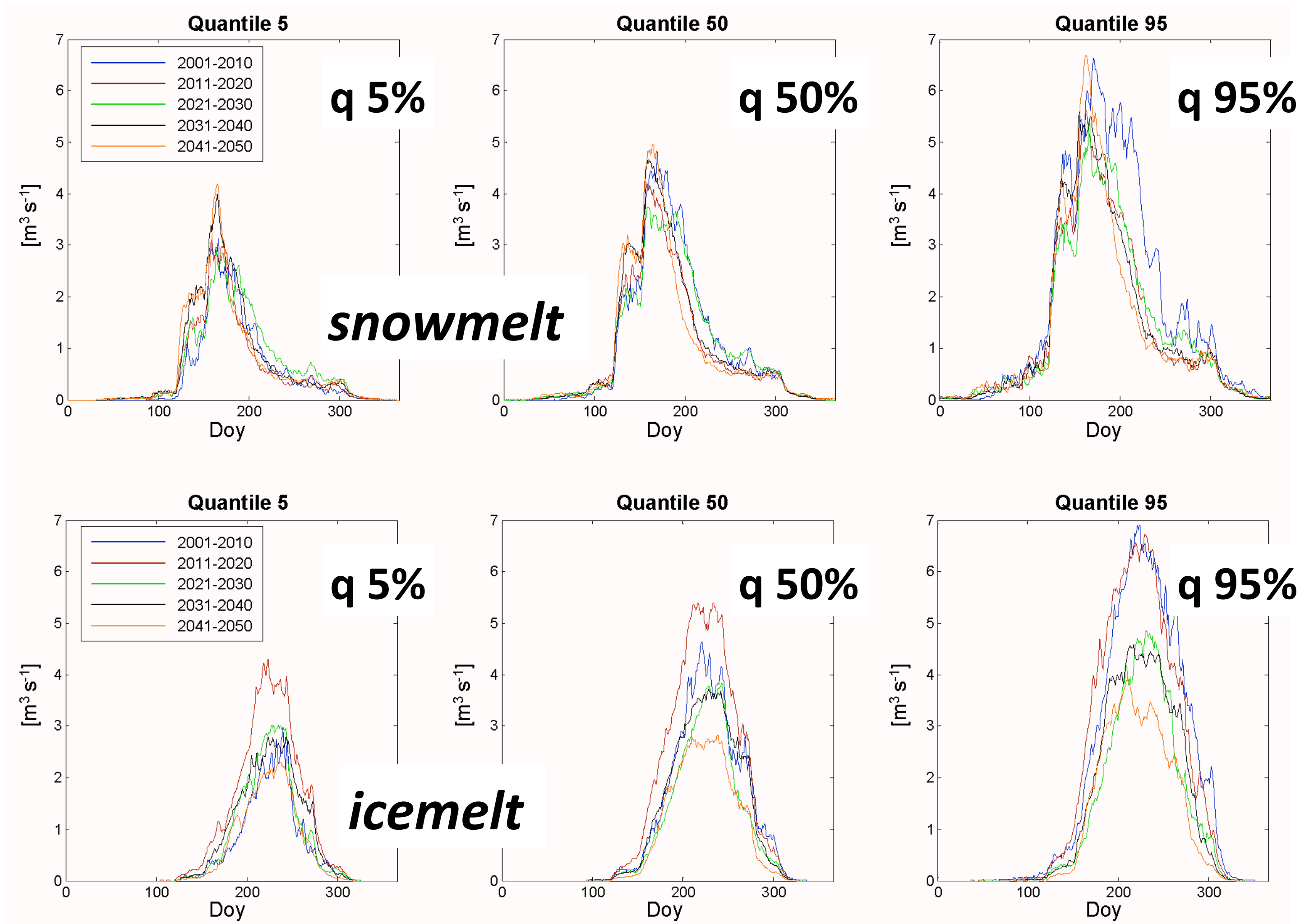
- **Impact of climate change (CC) on streamflow regimes**
  - *at reservoir locations (existing storage systems, downstream of glaciers)*
  - *in downstream reaches (existing run-of-river systems)*
  - *at locations where the hydropower potential (new systems) could be assessed*
- **Effects of enhanced glacier retreat**
  - *uncertain prediction due to unknown glacier bed topography, ice volume and its evolution*
  - *risk of increased siltation due to the retreat of glaciers and larger exposure debris-covered areas and increased erosion due to higher flood runoff*
- **Hydrological safety of dams (risk)**
  - *verification of design values → hydrological safety of main structure, safety organs and floodplain downstream against potentially higher flood risk*
  - *slope stability hazards → risk of slope failures and subsequent impulse waves (Vajont effect)*
- **Enhanced effects of streamflow regulation on river corridors**
  - *due to combined effect of changes affecting the natural regime and changes in HP operation → impact on renewal process of concessions*

# Example of glacier response, Rhonegletscher

quantiles computed as median of multi-member stochastic ensemble

**up to 2050**

- *no major changes of snowmelt in the early part of the season*
- *noticeable change of icemelt (the larger and thicker the glacier, the lower is the reduction)*
- *dependence on glacier morphology*




[Carenzo, PhD thesis #20616, ETH Zurich, 2012
DOI: 10.3929/ethz-a-007636154]

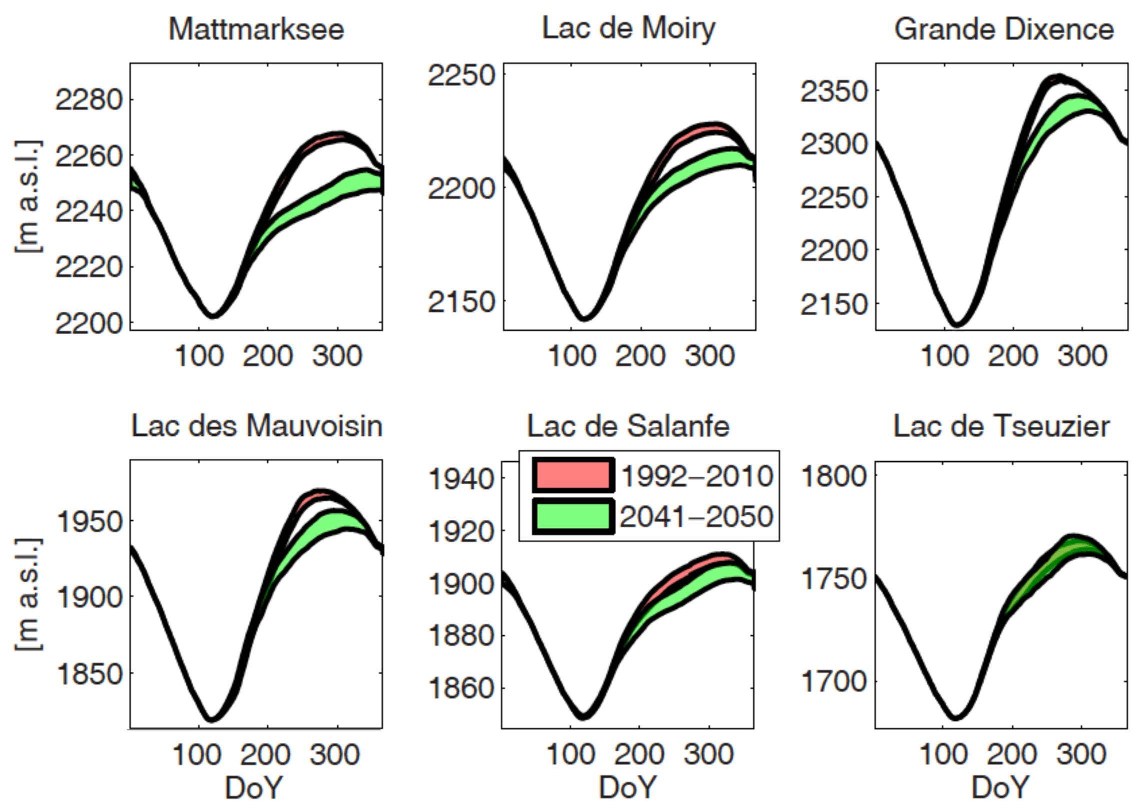
# CC impact on reservoir storage dynamics

### *2041-2050 vs 1992-2010 (control sc.)*

[Fatichi et al., JoH, 2015]

*Hypothesis*: operation ruled by a seasonally variable target level

- *in general significantly lower levels in summer and autumn (effect of reduced ice melt)*
- *changes larger than stochastic variability*
- *larger variability in future climates (higher dependence on precipitation variability)*




coloured band: values within the 10th and 90th percentile of the stochastic simulation

# How hydrology under CC affects HP

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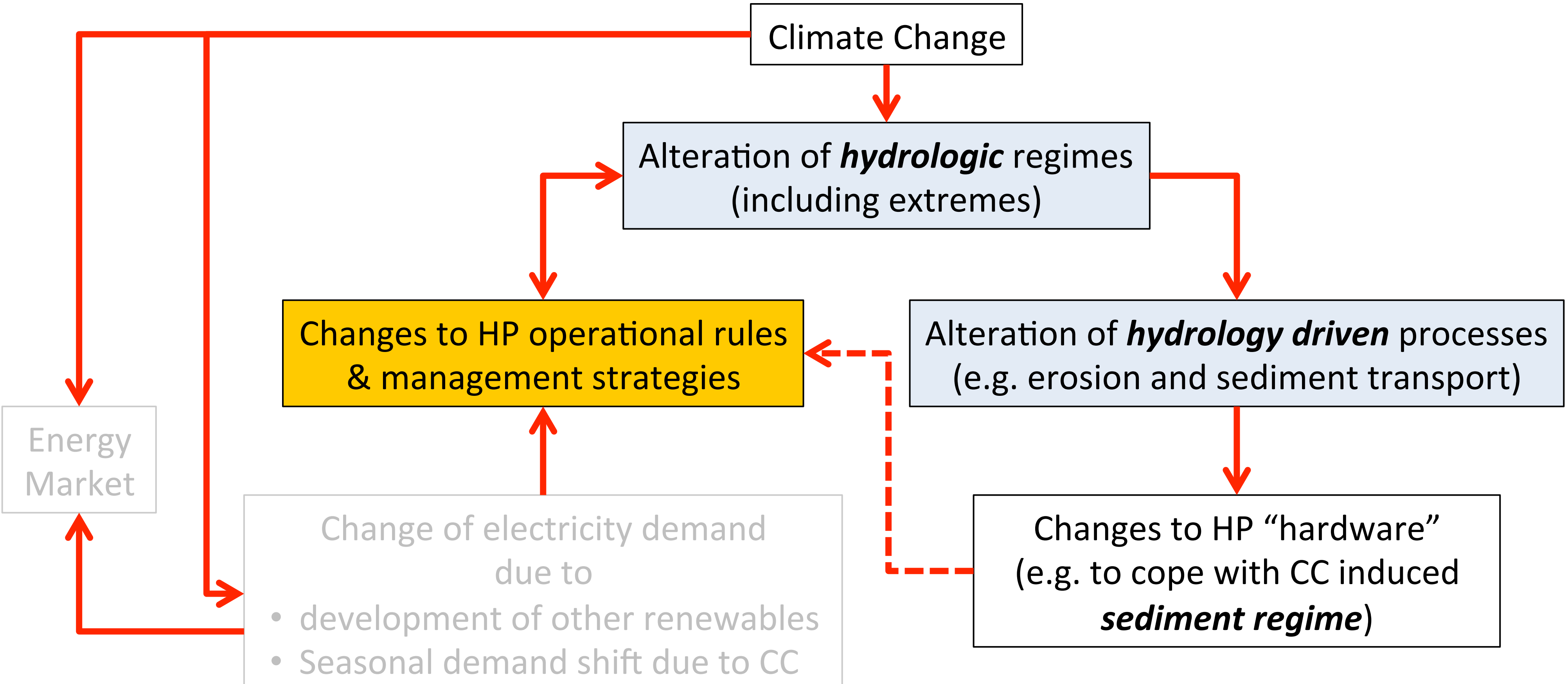
***interactions and causal relationships*** → **climate change as primary driver**



# Understanding future hydrology and its impact on HP

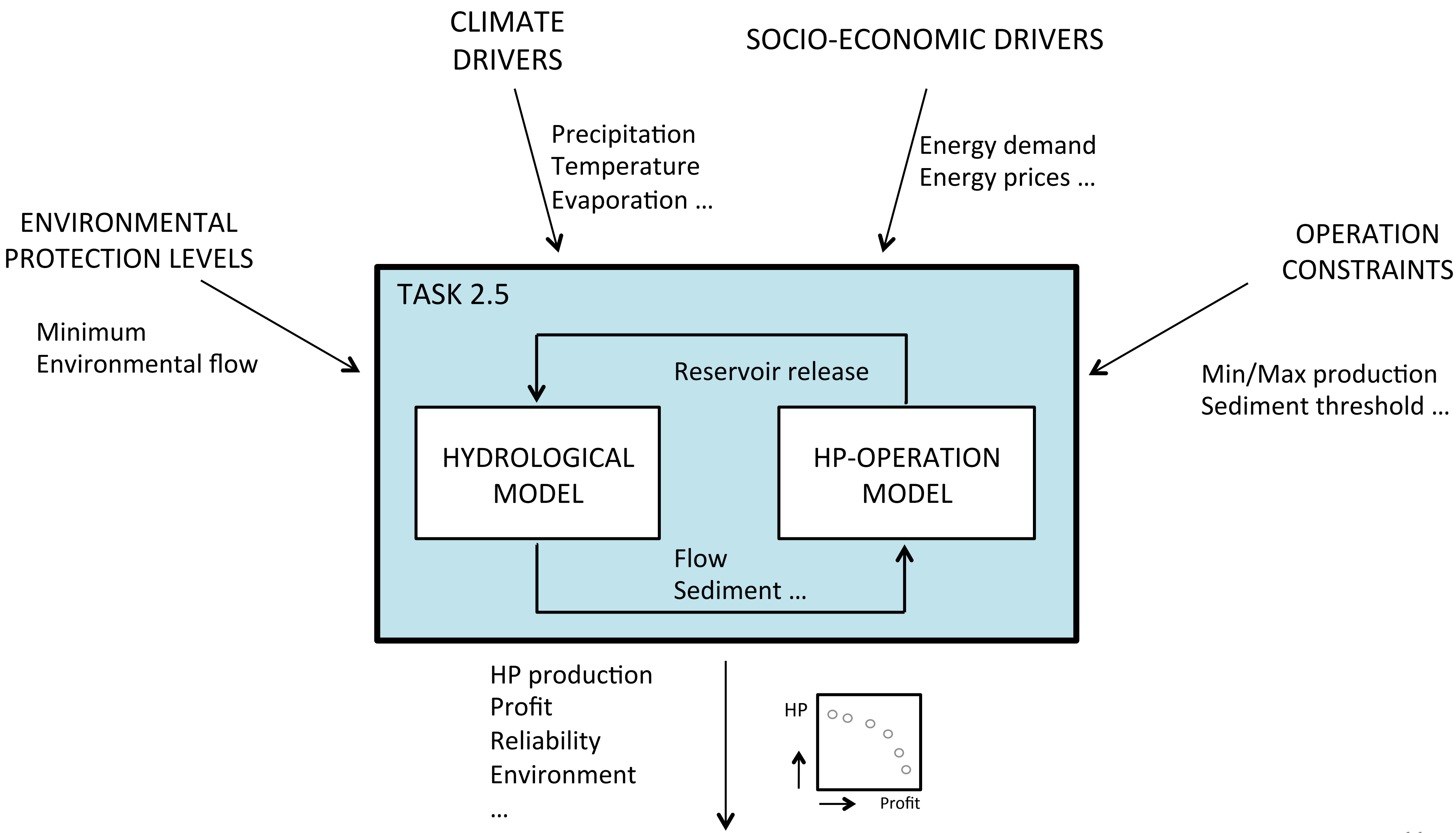
## INGREDIENTS

- **advanced physically based distributed hydrological model**
  - *hydrological processes + dynamic glacier mass-balance, sediment production and transport*
- **stochastic high resolution (space-time) climate forcing**
  - *to account for uncertainties due intrinsic climate variability and future climate*

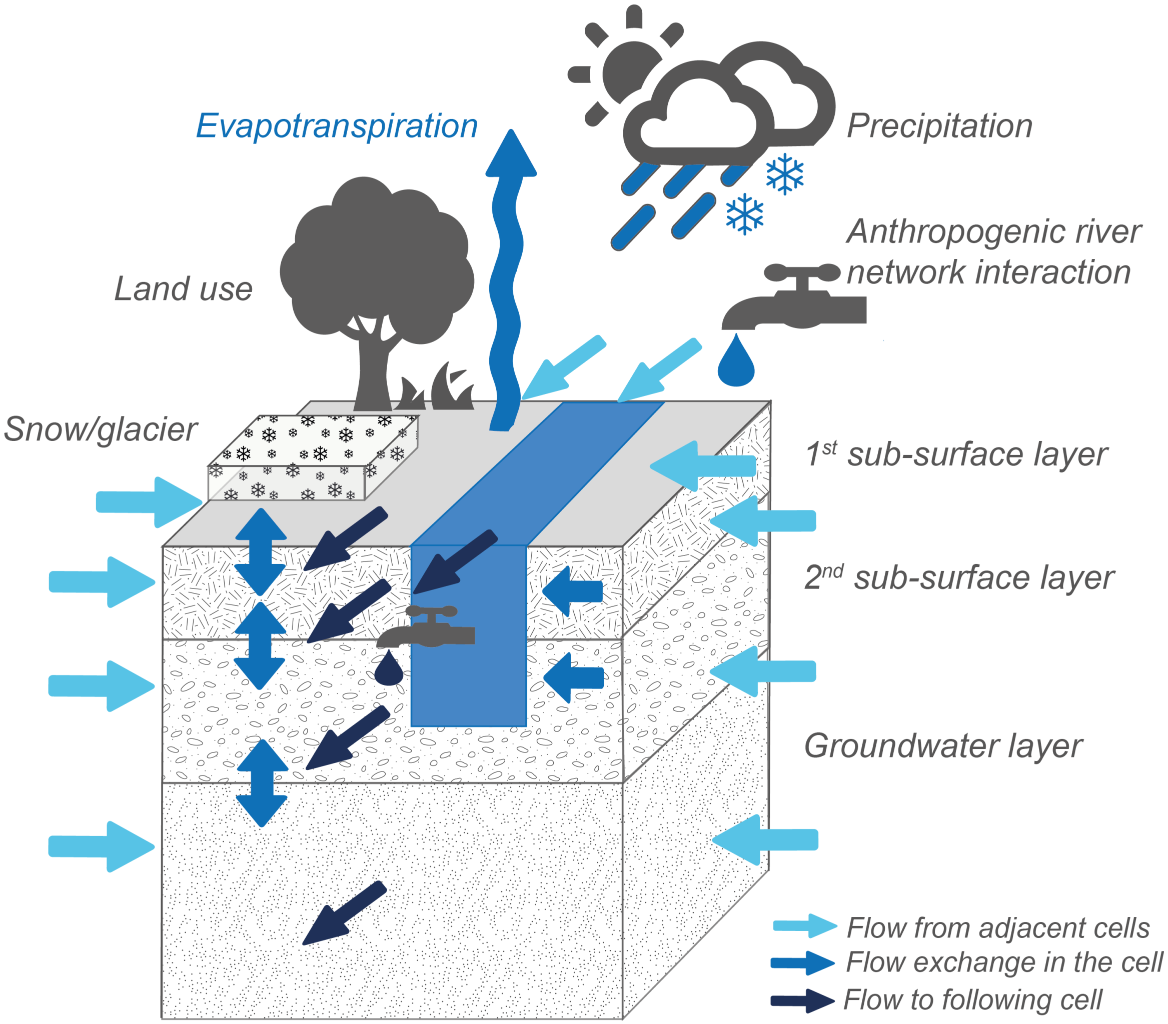
- **HP operation model**
  - *to investigate operation strategies conditional to changing hydrology, energy markets and other renewables*
- **feedback accounting framework**
  - *to assess the effects of operation strategies on basin hydrology*

**☞ integrated modelling framework ☜**

# Integrated modelling framework



# Hydrological modelling

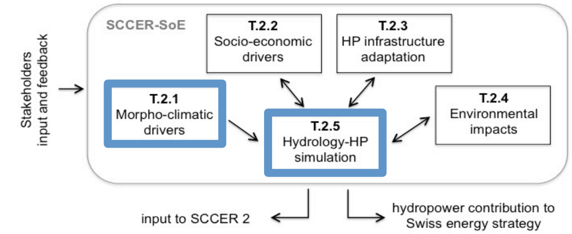


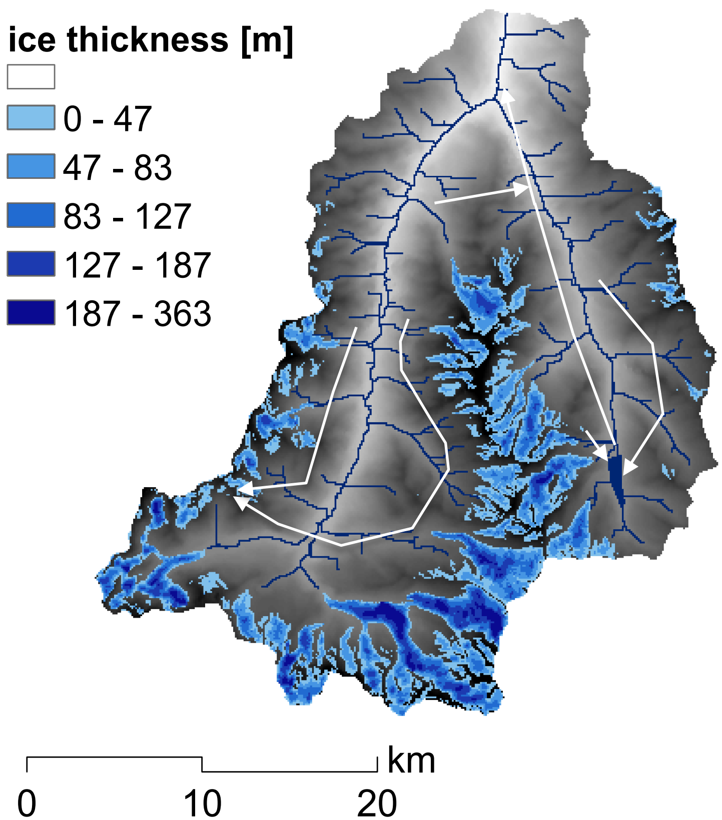

Topkapi-ETH key features:

- spatially distributed
- physically explicit
- snow-ice process dynamics
- geomorphological processes (sediment production and transport)
- anthropogenic structures (reservoirs, diversions, irrigation, and water supply)
- reasonably short computation time
- suited for stochastic analysis

# Example on Visp catchment + Mattmark hydropower system

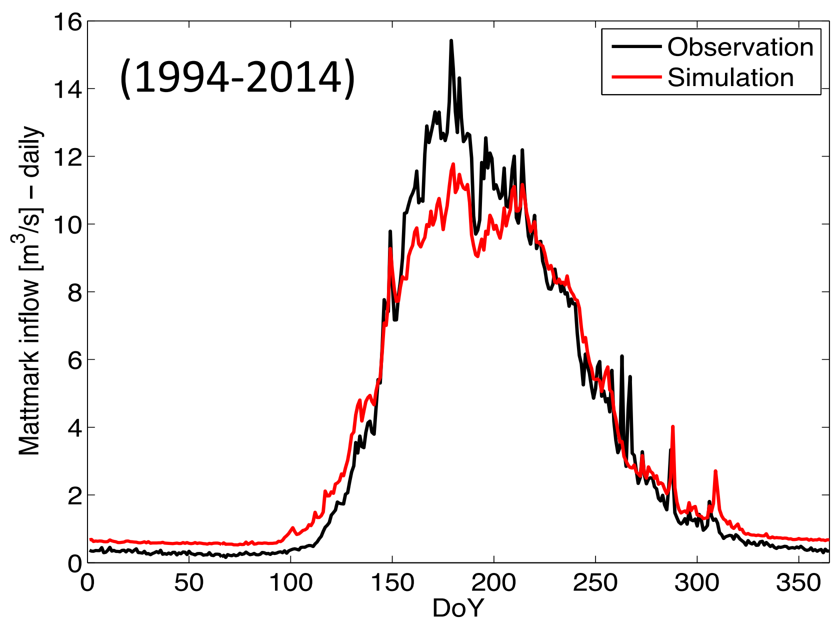
Joint effort of task 2.1 and 2.5




Topkapi-ETH hydrological model:

- spatial resolution: 100 m regular grid
- temporal resolution: hourly
- glacier thickness maps as in [2, 3]

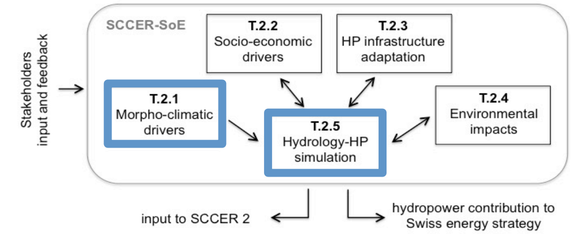



[2] Huss and Farinotti (2012). Distributed ice thickness and volume of all glaciers around the globe. Journal of Geophysical Research, 117,

[3] Fischer et al. (2014). The new Swiss Glacier Inventory SGI2010. Arctic, Antarctic and Alpine Research, 46(4), 933-945.

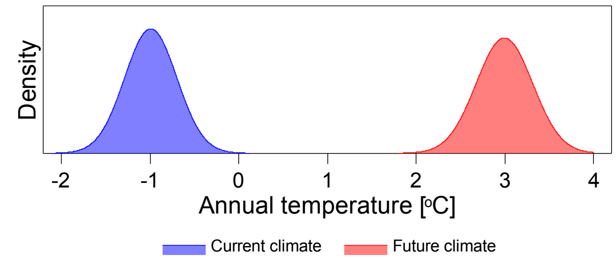
# Climate change impact on hydrology and reservoir operation

Joint effort of task 2.1 and 2.5

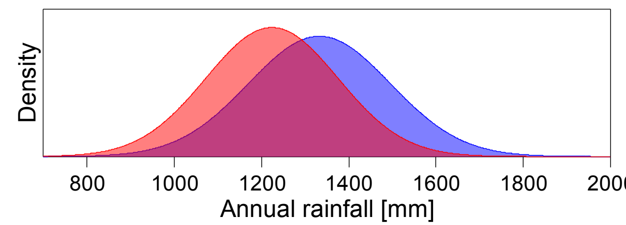



Preliminary results

The AWE-GEN-2d (Advanced WEather GENerator for 2-Dimension grid) is used for the statistical downscaling to formulate a high spatio-temporal resolution fields of precipitation and temperature.




2 multi-member ensembles representing the current climate (2004-2014) and the future climate (2071-2100) as in the official CH2011 climate scenarios.



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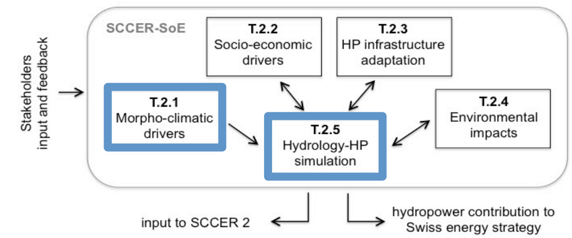


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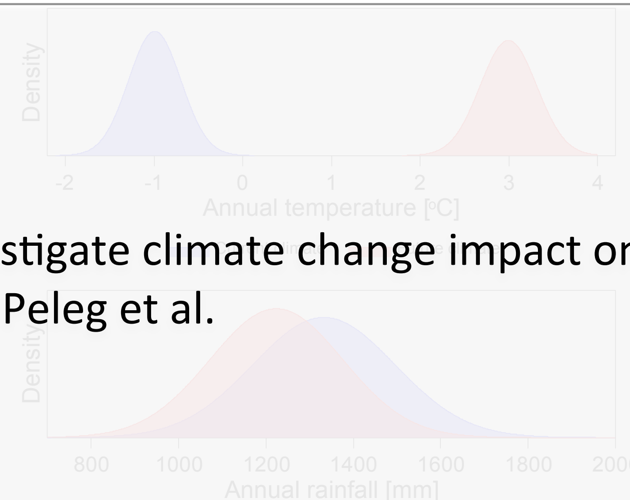


For more details:

Poster “Generation of very high resolution scenarios to investigate climate change impact on hydropower operation” (Task 2.1) by Peleg et al.

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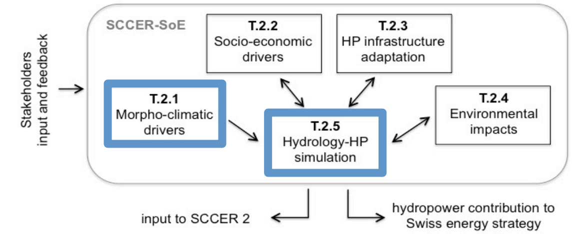


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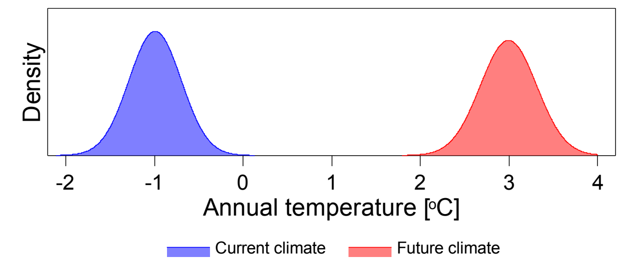


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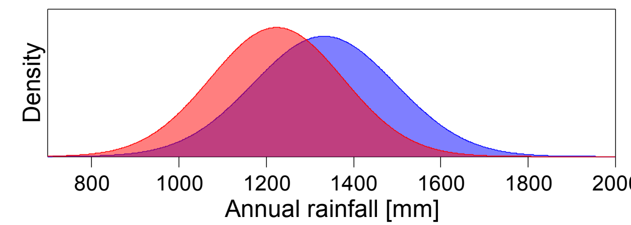
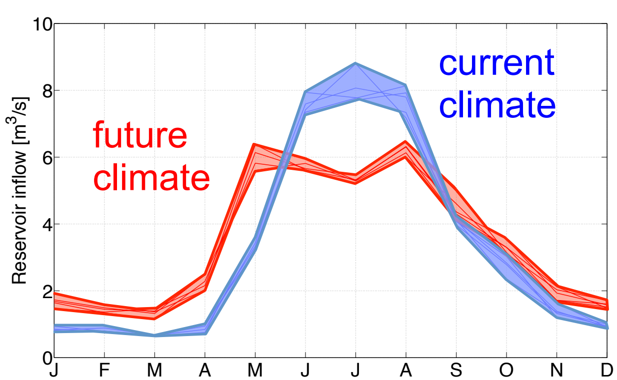
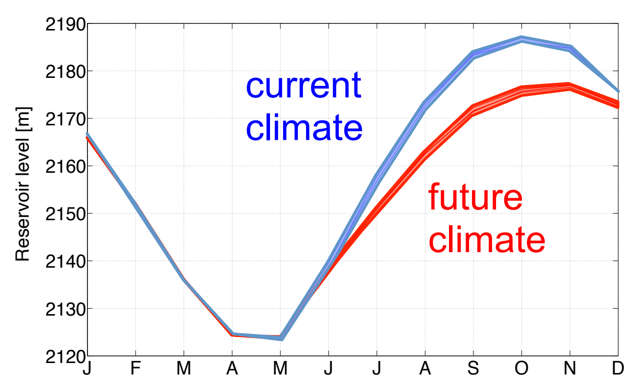



Topkapi-ETH is used to simulate the seasonal average trajectories of reservoir inflow and level.



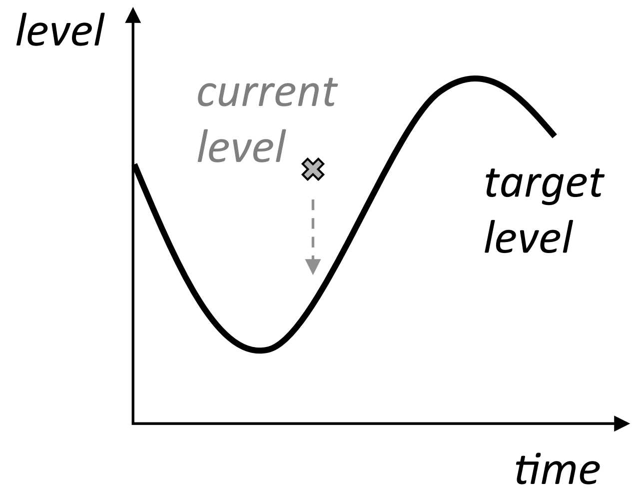




preliminary results

# Reservoir operation model: rule curve

Simplest model: rule curve

reservoir operation should follow a target level, corresponding to *normal operating conditions*




✓ Pros

- it can represents the seasonal water volume shift due to reservoir operation
- suited when the focus is on hydrology

✗ Cons

- it can not properly represent energy production
- not suited when the focus is on energy
- how do we define "*normal operating conditions*"? (especially when the context changes, e.g., climate change, new RES, no nuclear power plants)

# Reservoir operation model: control policies

More complex models: control policies

They account for relevant information available at the time the decision is taken (e.g., level of the reservoir, how much snow is accumulated in the basin, energy demand/price, …)

Optimal control problem:

- reservoir operators are rational agent maximizing a utility function (e.g., revenue)

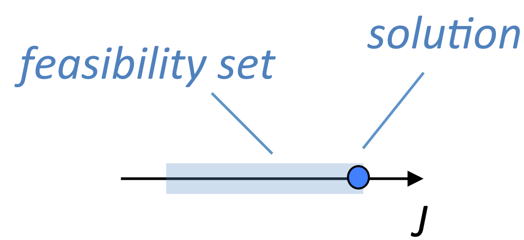
*objective* $\max_{m_t(\cdot)} J \qquad J = \lim_{h \to \infty} \mathop{E}_{\epsilon_1^h \sim \phi} \left[ \sum_{t=0}^{h-1} \gamma^t g_t(s_t, u_t, \epsilon_t) \right]$

*mass balance* $s_{t+1} = f(s_t, u_t, \epsilon_t)$

*control variable* $u_t = m_t(s_t)$

*feasibility set* $u_t \in U_t(s_t)$

*exogenous variable* $\epsilon \sim \phi(\cdot)$

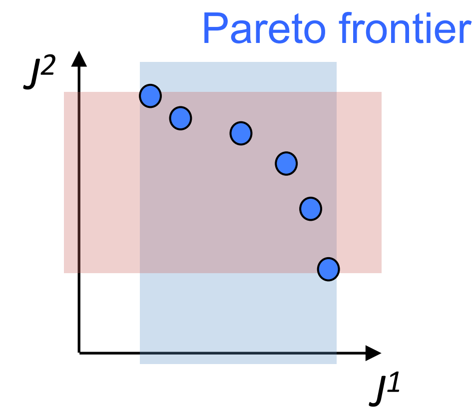


# From single to multi objectives

Why?

- There are many stakeholders and points of view:
  - national energy strategy
  - supply security
  - hydropower companies perspective
  - environment conservation

- Relative importance of the objectives may change in time



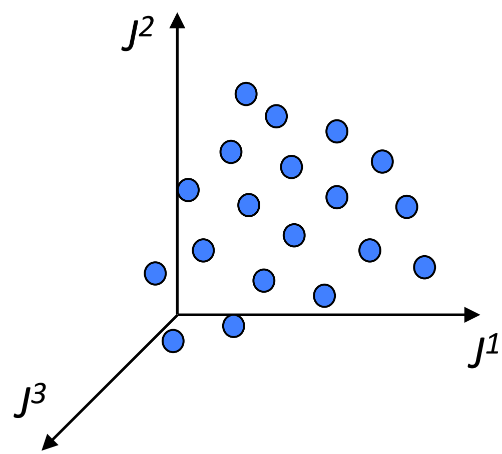

$$\max_{m_t(\cdot)} \mathbf{J} = |J^1 J^2 \cdots J^n|$$

$$s_{t+1} = f(s_t, u_t, \epsilon_t)$$

$$u_t = m_t(s_t)$$

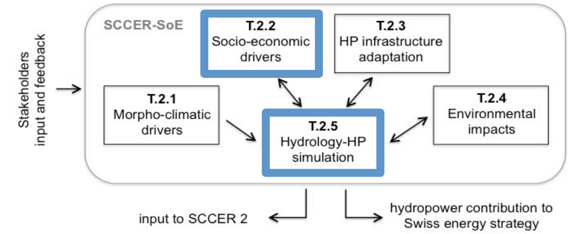
$$u_t \in U_t(s_t)$$

$$\epsilon \sim \phi(\cdot)$$



# Example of control problem for Mattmark operation

Joint effort of task 2.2 and 2.5




two objectives:

- $J^1$: production
- $J^2$: revenue

$$\max_{m_t(\cdot)} \left[ J^1 \, J^2 \right]$$

$$s_{t+1} = f(s_t, u_t, \epsilon_t)$$

$$u_t = m(t, s_t)$$

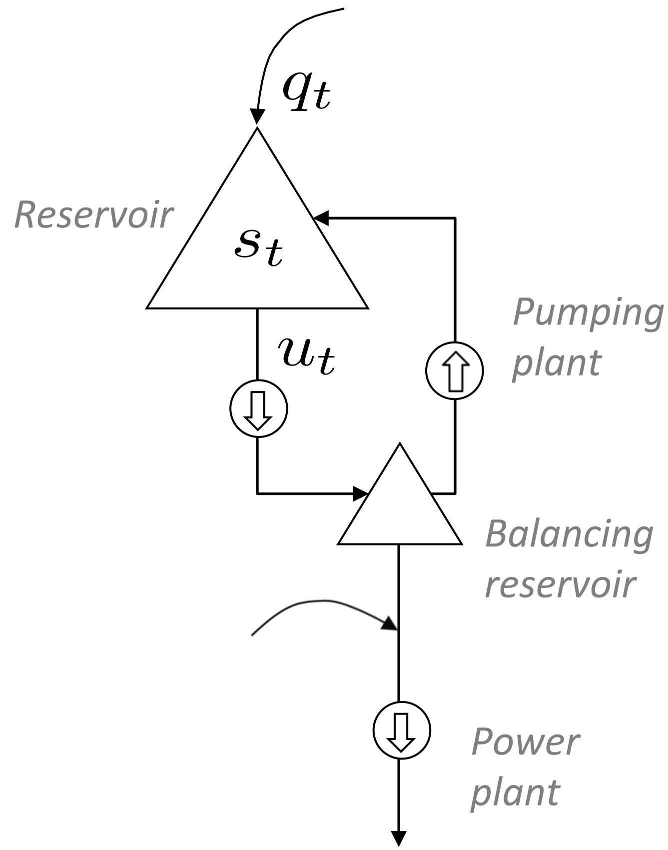
$$u_t \in U_t(s_t)$$

$$\epsilon_t \sim \phi(\cdot)$$

one control variable:
daily reservoir release

two exogenous variables:

- reservoir inflow
- energy price




Modeling simplifications so far:

- pumping is not considered
- perfect knowledge of inflow
- perfect knowledge of energy price

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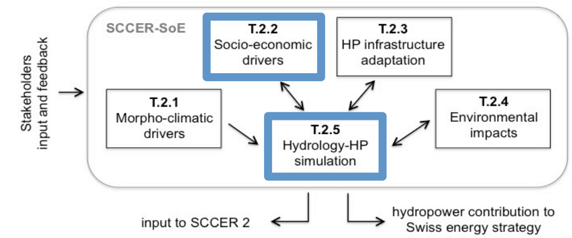
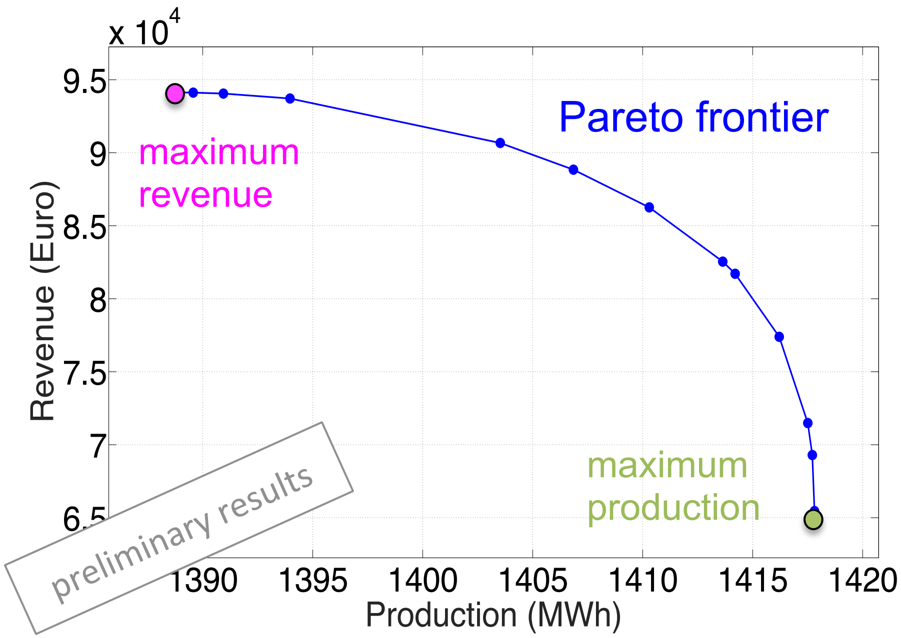
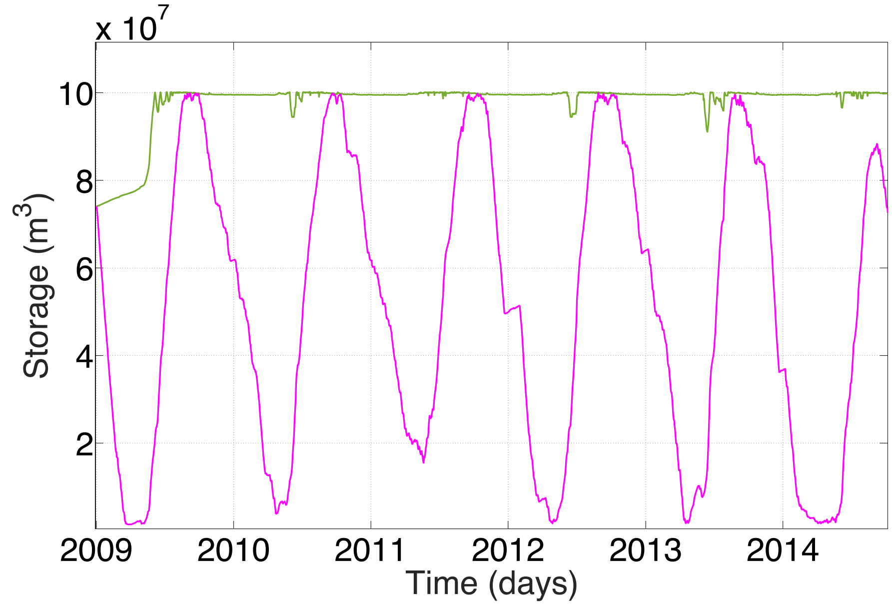
Joint effort of task 2.2 and 2.5




Solution of the (simplified) deterministic control problem on the historical period 2009-2014




- How much energy can be produced? And what is the associated cost?
- How does the tradeoff change when considering more objectives (e.g., environment conservation)?
- What is the effect of different energy markets (energy-only market, reserve market, …)?

# Future directions

- Integrate reservoir operation control policies in hydrological model
- Assess the joint effects of hydro-climatic and socio-economic drivers on hydropower system operation
- Design robust reservoir operating policies to future system uncertainty
- Assess the effects of present and future reservoir operating polices on the downstream river corridors
- Upscale the analysis (to other case studies and towards the regional scale)

for more information: posters in Task 2.5