Task 2.4

Task Title

Environmental impacts of future hydropower operating conditions

Research Partners

Swiss Federal Institute of Aquatic Science and Technology (EAWAG), Applied Hydroeconomics and Alpine Environmental Dynamics (AHEAD) at EPFL, Chair of Hydrology and Water Resources Management (HWRM) at ETH Zurich, Laboratory of Hydraulics, Hydrology and Glaciology (VAW) at ETH Zurich, Institute of Earth Surface Dynamics (Idyst) at University of Lausanne

Current Projects (presented on the following pages)

Optimizing environmental flow releases under future hydropower operation (HydroEnv)
C. Gabbud, G. Bergami, P. Chanut, A. Niayifar

Mobile-bed flood analysis of the Sarine in view of Artificial Flood monitoring
J. Durand-Gasselin, S. Stähly, P. Manso, A.J. Schleiss

Ecological impacts of small-scale run-of-river hydropower plants
K. Lange, S. Di Michelangeli, Y. Kahlert, J. Hellmann, C. Trautwein, C. Weber, J. Brodersen

Assessing the impact of pumped-storage operation on lake stratification
U.G. Kobler, M. Schmid

Hydro-peaking mitigation measures: performance of a complex compensation basin considering future system extensions
P. Meier, M. Bieri, P. Manso, S. Schweizer, A. Fankhauser, B. Schwegler

Quantifying weighted usable area produced by macro roughness elements in river flow and habitat simulations
H.J. Oldroyd, A. Niayifar, P. Perona

Task Objectives

In view of climate change and energy market dynamics, this task addresses the response of aquatic ecosystems to future streamflow alterations resulting from

- modified hydropower operating conditions and improved flexibility
- the increasing development of small hydropower plants (SHPPs), by means of which the Energy Strategy 2050 aims at an additional power generation of 1 to 2 $TWh \cdot yr^{-1}$.

A better understanding of the ecological effects following operational and infrastructural measures will allow to develop improved environmental impact strategies for a given power production. In particular, this will be achieved by

- optimizing the spatial distribution of power production in a network of HPPs and SHPPs at the catchment scale

- developing new criteria for environmental flows, which minimize negative environmental impacts by mimicking natural flow dynamics, while maintaining or increasing hydropower production.

Interaction Between the Partners – Synthesis

- The research institutes involved in this task are jointly working in the NRP70 project HydroEnv (see poster by Gabbud et al.).

Highlights 2016

- It was shown for some case studies that a dynamic environmental flow regime can significantly improve ecological indicators in the residual flow stretch without reducing the economic benefit. A software tool was developed with a graphical user interface, which allows to assess the effects different environmental flow policies for specific case studies. The software is publicly available for download on the SCCER-SoE website.
- Improved environmental indicators for the assessment of environmental impacts in multi-objective optimization models are currently being developed.
- The local impacts of small hydropower plants were investigated in a study including seven field sites. Observed impacts were most obvious in the residual flow reaches, where the in-stream habitat was shown to reduce trout body condition, which could be partially explained by changes in prey availability and their feeding behaviour.
- A tool assessing potential configurations of multiple run-of-river power plants within a river net-work with respect to the extinction probability of migratory species was developed. It was shown that a careful selection of sites for power plants minimises the extinction probability, while not compromising the total power production or investment costs.

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Optimizing environmental flow releases under future hydropower operation (HydroEnv)

Gabbud Chrystelle, Bergami Gianluca, Chanut Pierre, Niayifar Amin

Lead by Prof. Burlando P (ETHZ) and supervised by Lane SN (UNIL), Molnar P (ETHZ), Robinson C (EAWAG), Perona P (UoE), Battin TJ (EPFL)

1. Motivation

This SNF project is part of the NRP 70 Program – Energy Turnaround: Scientific and technological aspects.

The global aim is to provide new and advanced methods for the analysis of medium- to long-term **tradeoffs between hydropower production and eco-hydrological dynamics** in Alpine catchments under current and projected future climate.

2. Aims and synergies

UNIL | Université de Lausanne
Institut des dynamiques de la surface terrestre

Establishing the long-term impacts of flow abstraction upon instream ecology where sediment delivery is maintained but transport capacity is reduced, with a particular focus upon macroinvertebrates and geomorphological changes

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Developing a new three-fold model unifying surface water, groundwater and vegetation stress, able to predict the river behavior as it is pervaded with different discharge regimes

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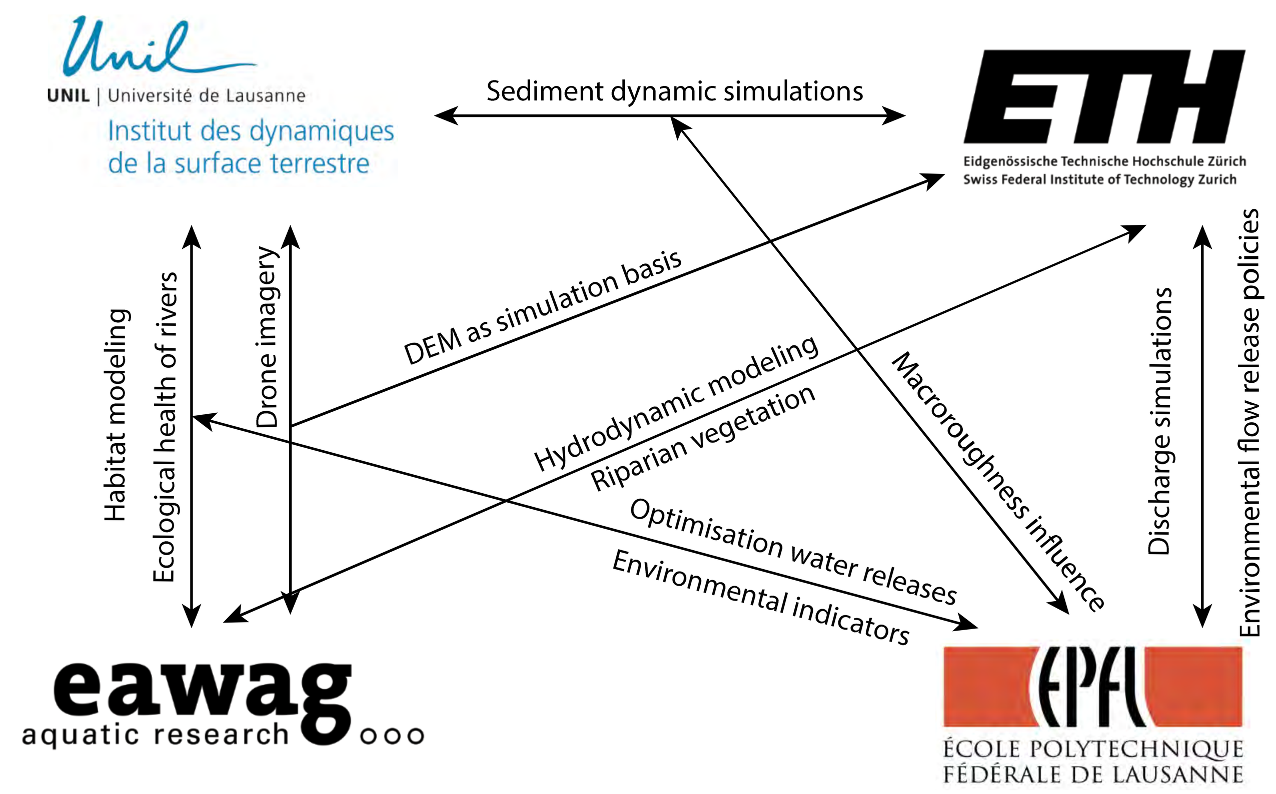
aquatic research

Identifying the processes linking hydrology and the structure and function of the floodplain aquatic ecosystem, investigating the relationships between different attributes of the flow regime and the composition of benthic algae and macroinvertebrate communities

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Developing an analytical and numerical framework on the basis of which dynamic flow redistribution policies, which balance hydropower generation and riverine ecosystem needs can be quantified, defining operational policies to generate dynamic environmental flows



We also have **collaborations with national leaders in hydropower production** (OFIMA; HYDRO Exploitation SA, Alpiq), with different **environmental associations** (WWF, Pro Natura, Fishing Federal Association) and **cantonal authorities** (Valais and Ticino).

3. Study sites

Borgne d'Arolla (VS)

- Water intake
- Irregular flushing flows
- Sediment trapping and flushing

→ Sediment deposition processes
→ Sediment wave propagation
→ No aquatic habitat

Maggia River (TI)

- Reduction of flows
- Floods maintained
- Small sediment disruption

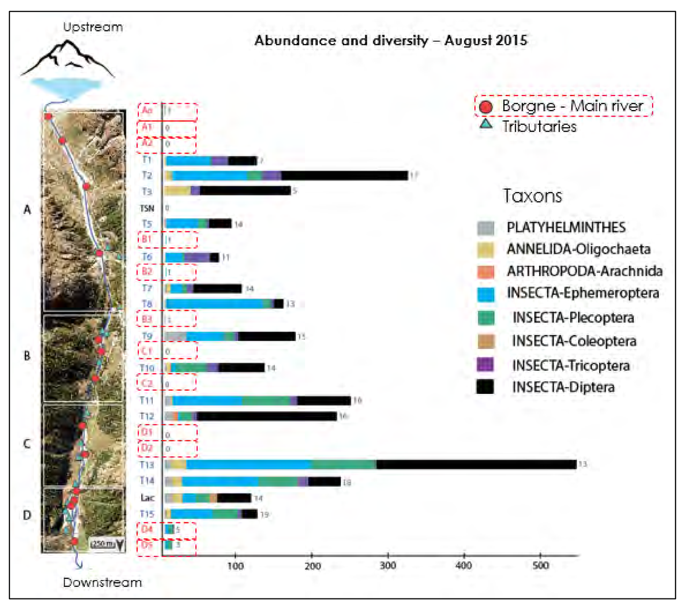
→ Riparian vegetation processes
→ Decrease in aquatic habitat
→ Water stress in riparian zone

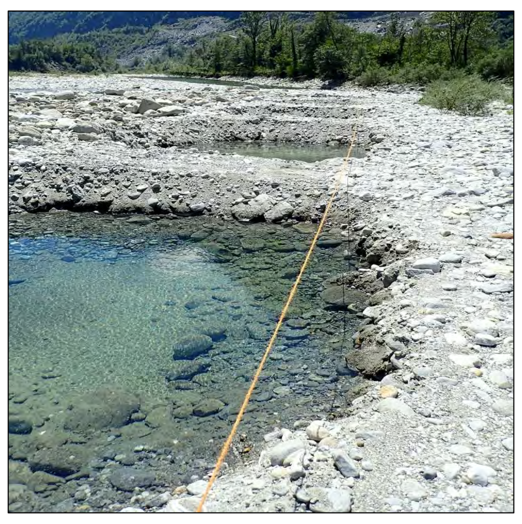
4. Methods

- Fluvial geomorphology and river processes
- Remote sensing (LiDAR, drone and airplane aerial imagery)
- Macroinvertebrate sampling
- Biofilm collection
- Habitat studies and modeling
- Hydrology, watershed and hydraulic modeling
- Riparian vegetation dynamics modeling
- Strategies of dynamic environmental flows (DEFs)

5. Main provisional results

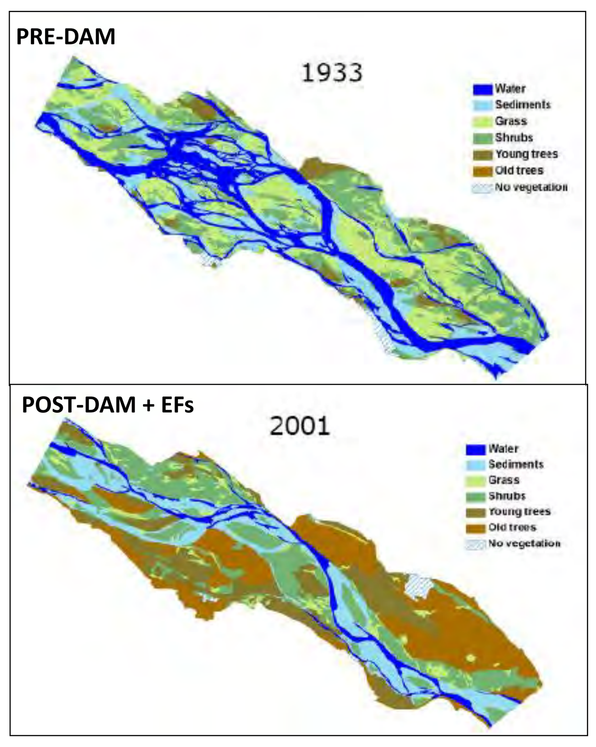
a. The Borgne d'Arolla is largely **void of life** as compared with unregulated tributaries, suggesting two driving factors: (1) stream temperature; and (2) sediment delivery due to intake purging of sediment, which leads to **substantial channel instability**, as shown by the morphological changes from DEM.

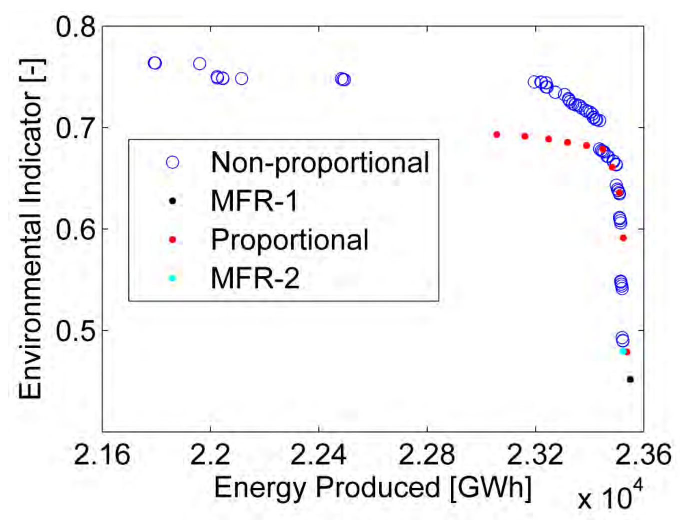




b. In the Maggia, we found that an **interaction between environmental forcing and biotic interactions constrain macroinvertebrate community** assembly, and the relative importance of these drivers varies among seasons, with a strong biotic interaction phase in summer.

c. The diffusion and type of riparian vegetation before and after the construction of the dam differ significantly, as **the braided character of the Maggia river has dramatically decreased**. Grass was replaced by more mature plant colonies and **the overall age of vegetation in the basin has increased over time**. The result is a stasis in the location of gravel bars.





d. **Dynamic environmental flow releases** (non-proportional) allow for a broader spectrum of globally-efficient performances of the dammed system compared to constant minimum flow release operational policies, found to be mainly due to a **better use of the reservoir** storage dynamics, which enables the capture and lamination of flood events while recovering part of the flow for energy production.

We expect the results to **provide a basis for guidelines to hydropower producers and legislators** regarding, as much as possible, this overall aim.

6. Publications

Gabbud C. and Lane S.N. (2016). Ecosystem impacts of Alpine water intakes for hydropower: the challenge of sediment management. *WIREs Water,* 3(1), 41-61. [10.1002/wat2.1124].

Niayifar A. and Perona P. (accepted). Searching Pareto-efficient dynamic environmental flows by means of nondominated sorting genetic algorithms II. *River Flow 2016*.

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70 NRP Energy Turnaround
National Research Programme

Mobile-bed flood analysis of the Sarine in view of Artificial Flood monitoring

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Problematic and Objectives:

Problematic: Rivers downstream of dams are often subject to residual flow or hydropeaking conditions that have negative impact on the morphological diversity and the structural stability of the river's ecosystems. Furthermore, dams may cause a sediment deficit which likely lead to incision of the riverbed and vegetation establishment in the floodplain.

Objectives:

- Assess the effects of an experimental flood and resulting sediment transport on the reactivation of sediment dynamics;
- provide sediment replenishment to create new habitats for aquatic organisms.

Methods:

- **1D-2D Coupled numerical simulations** with the software BASEMENT (Fig. 1) have been conducted to provide hydraulic information and predict the sediment transportation in the Sarine river during the artificial flood event

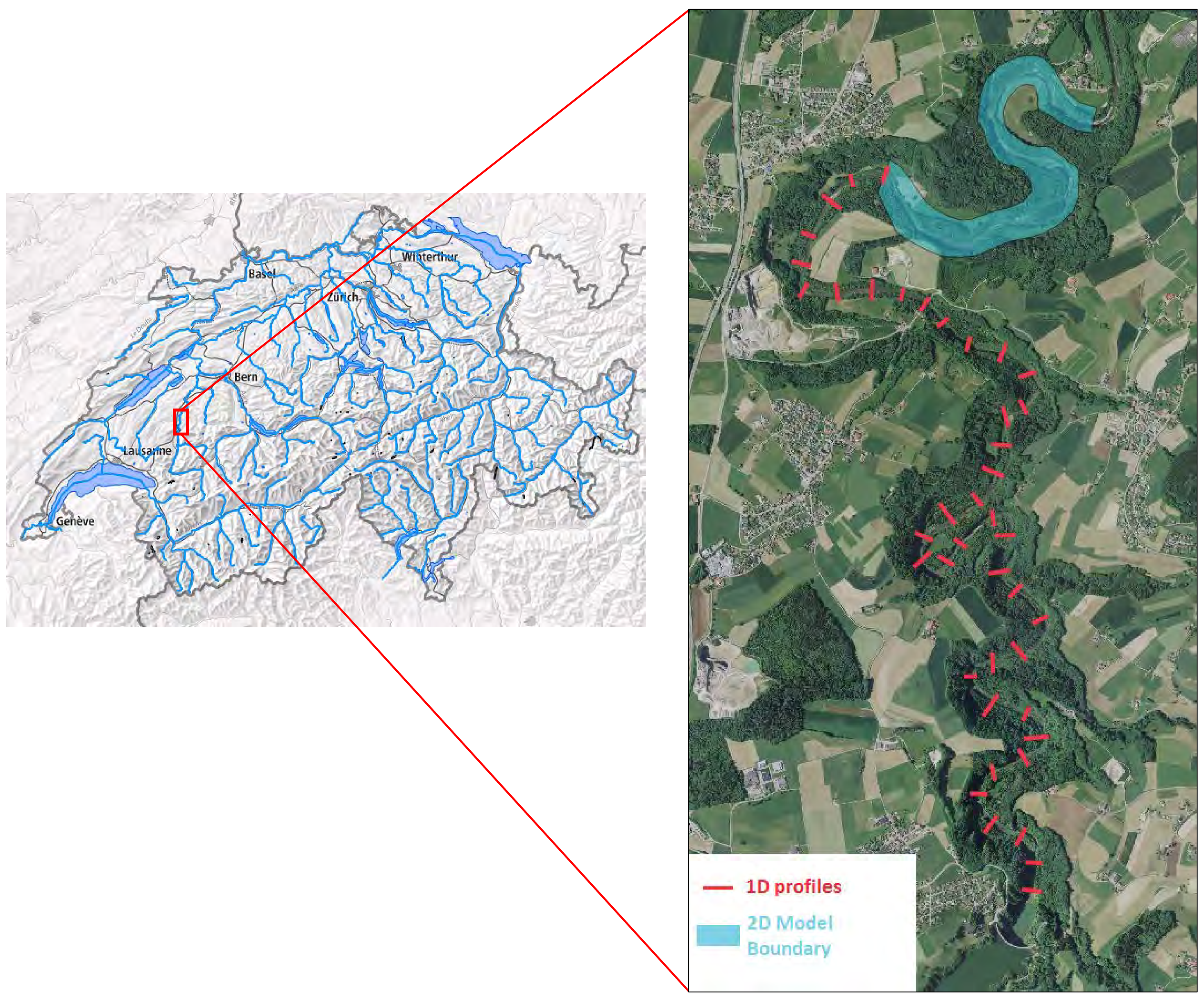

Figure 1: Study site location and model boundaries.

- **Sediment replenishment:** A sediment volume of 1000 m³ has been deposited in the upstream part of the study site, along with a sample of 500 pebbles equipped with Radio Frequency Identification (RFID) tracers to observe the sediment transport caused by the experimental flood.

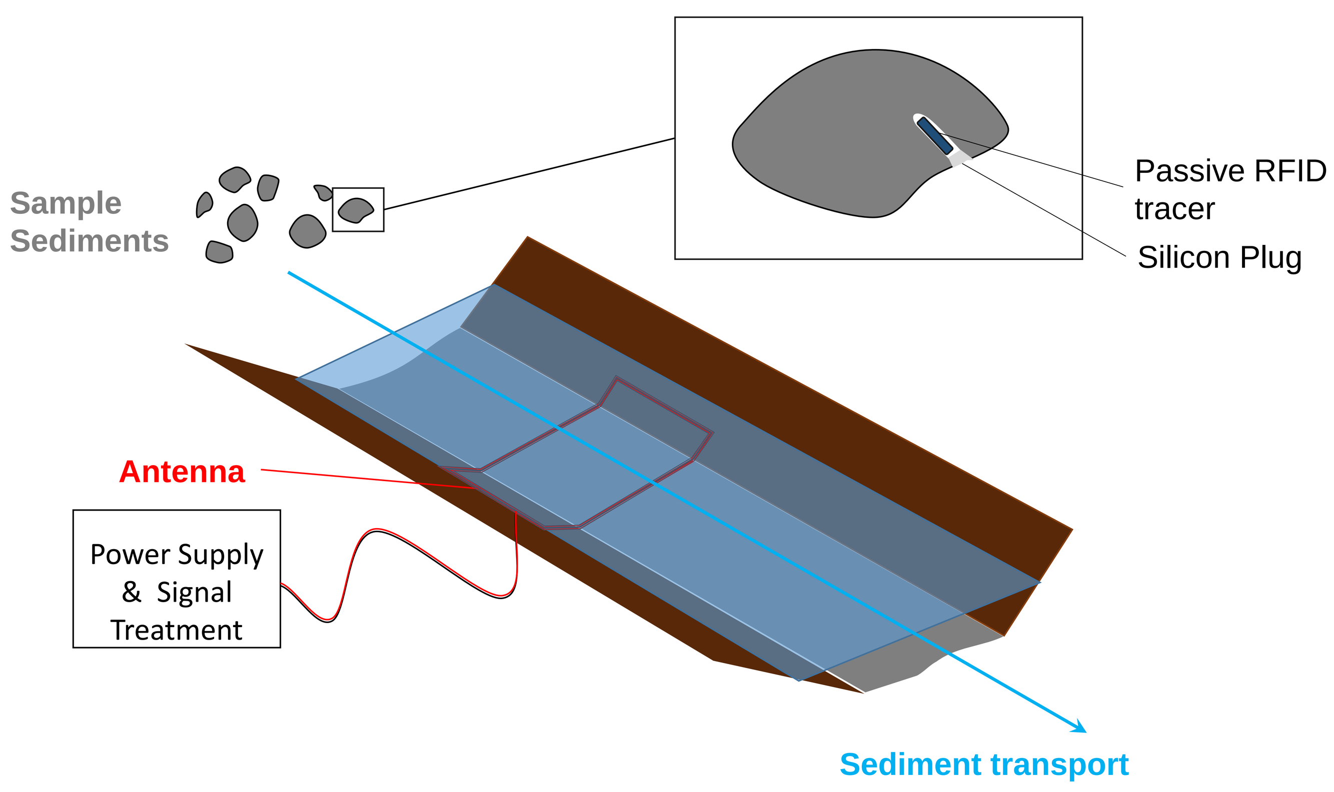

Figure 2: Antenna Design

A system of stationary antennas (Fig. 2) allows the detection of the passing tracers. In total three such antennas will be installed. The results could be used to optimized the hydrograph of a future the experimental flood.

Results:

The 2D numerical model used for the simulations has the following characteristics :

- 14922 nodes;
- 29209 triangular elements;
- mean element area : 17 m²
- total model area: 497 340 m²

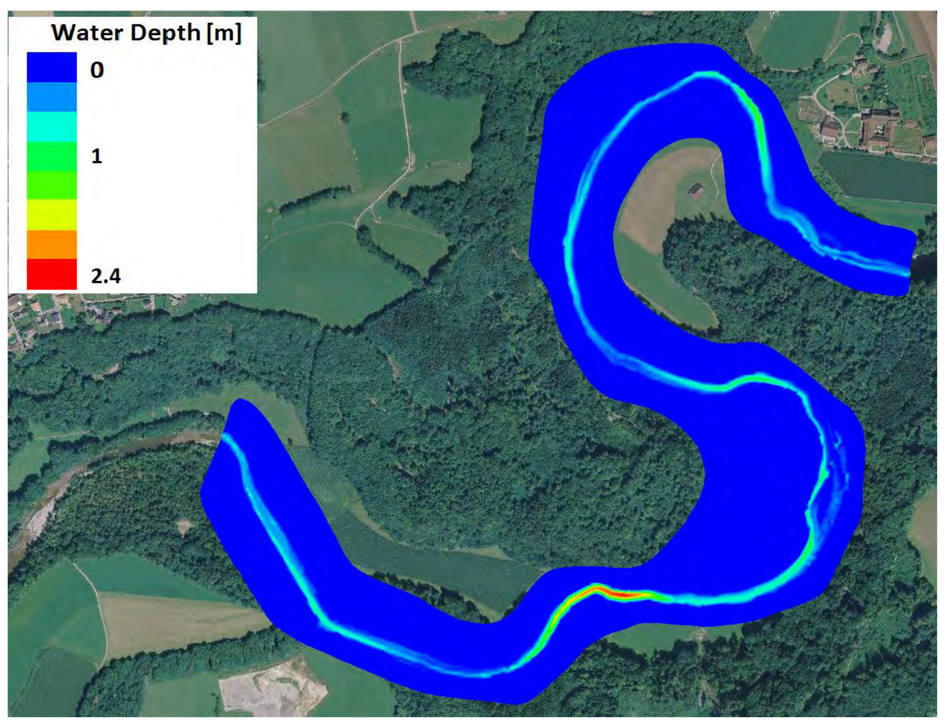

Figure 3: Simulation results of water Depths **before the flood**

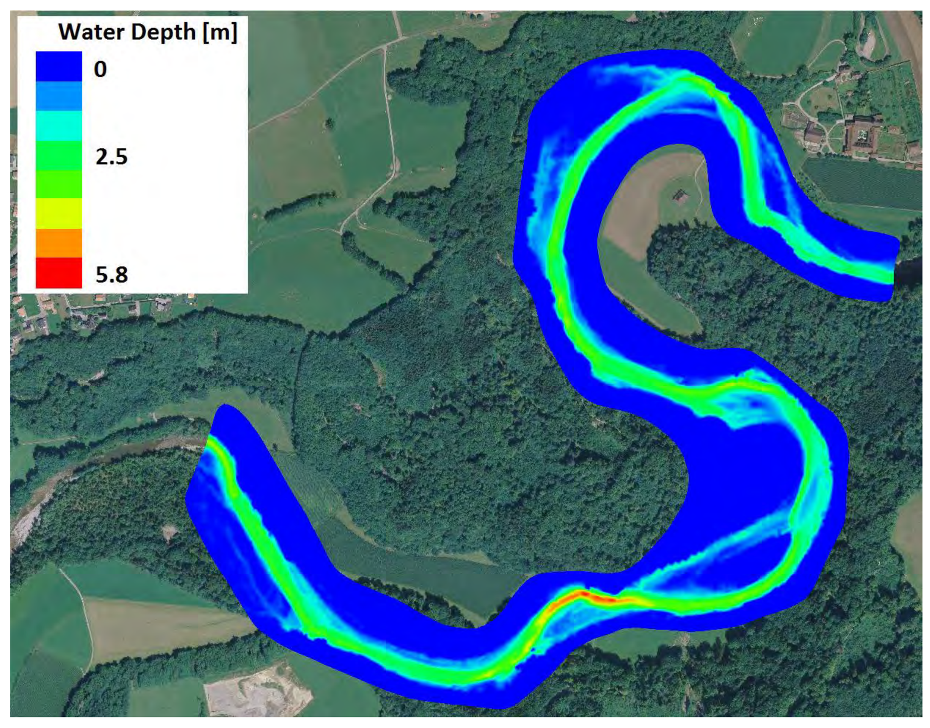

Figure 4: Simulation results of water Depths **after the flood**

- The numerical simulation results allow the prediction of dry areas which will be flooded during the event (Fig. 3 and 4). A biological study before and after the flood will provide information about the biological value of this.

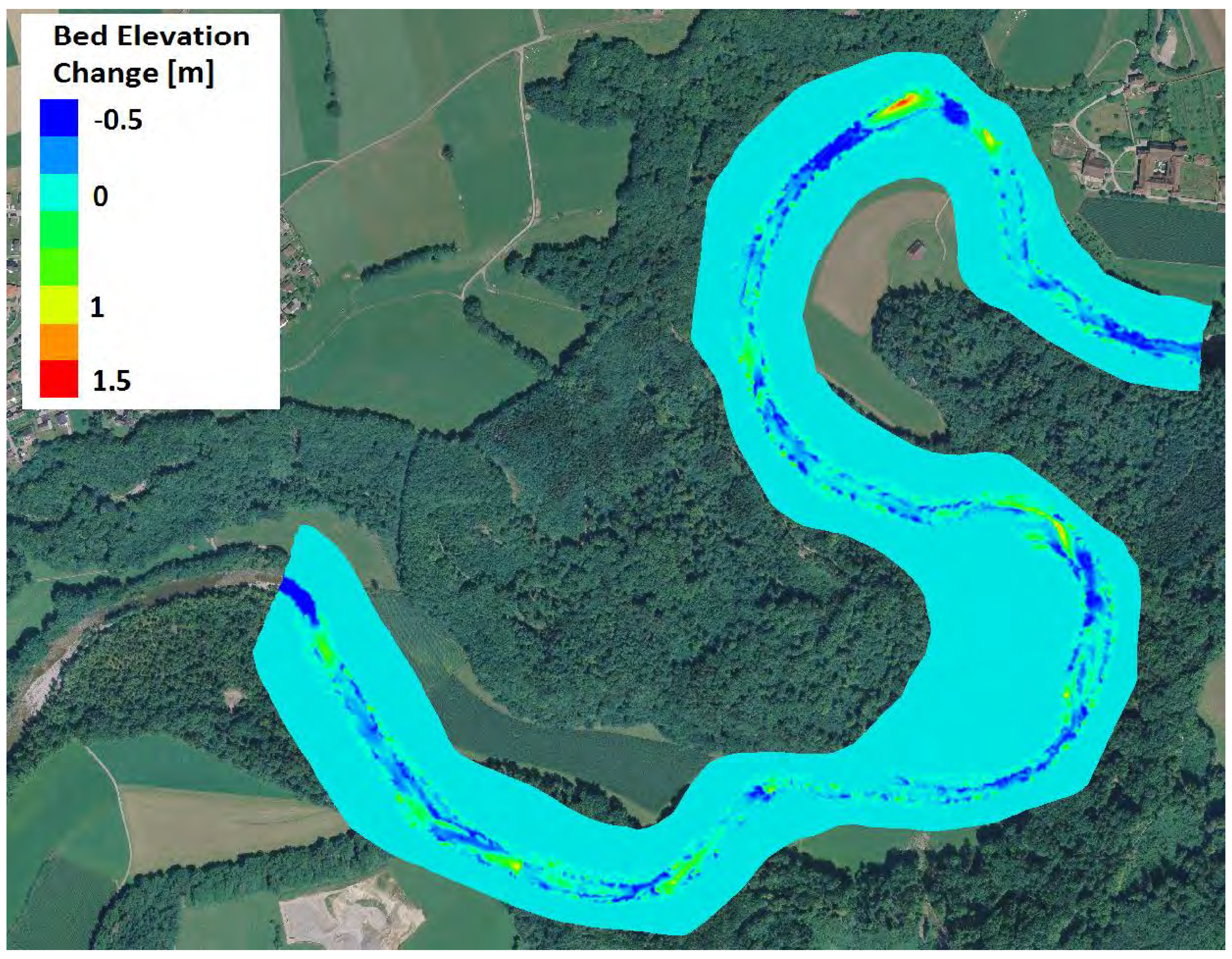

Figure 5: Simulation results of bed elevation change during the flood

- Fig. 5 shows where erosion and sediment deposit is expected: sediment deposition occur mainly at the end of a meander.
- The change in hydro-morphological diversity can be assessed by the calculation of the Hydro-Morphological Index of Diversity (HMID, Gostner 2012). The numerical simulation from before the event results in an $HMID_1$ of 8.6 and after the event in a $HMID_2$ of 10.4. This indicates, that the habitat diversity is expected to rise due to the experimental flood event.

Conclusion and Outlook:

- The experimental flood is expected to reactivate sediment dynamics and increase the morphological and flow diversity in the downstream river reach, bringing the river closer to natural flow conditions.
- Numerical Simulations provide predictive information on the change in the morphological and flow diversity, but require further calibration in particular for bed load transport.
- The experimental flood will take place during the 14th and 15th of September, and the radio frequency tracking system of sample stones is expected to provide reliable information on the sediment transport to be compared with the numerical simulation results.

References

1. Gostner W. (2012), The Hydro-Morphological Index of Diversity: a Planning Tool for River Restoration Projects, EPFL Thesis No. 5408
2. Faeh R. et al., (2011), System Manuals of BASEMENT, VAW publication No. 3047

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Ecological impacts of small-scale run-of-river hydropower plants

Katharina Lange, Sergio Di Michelangeli, Yvonne Kahlert, Johannes Hellmann, Clemens Trautwein, Christine Weber, Jakob Brodersen*

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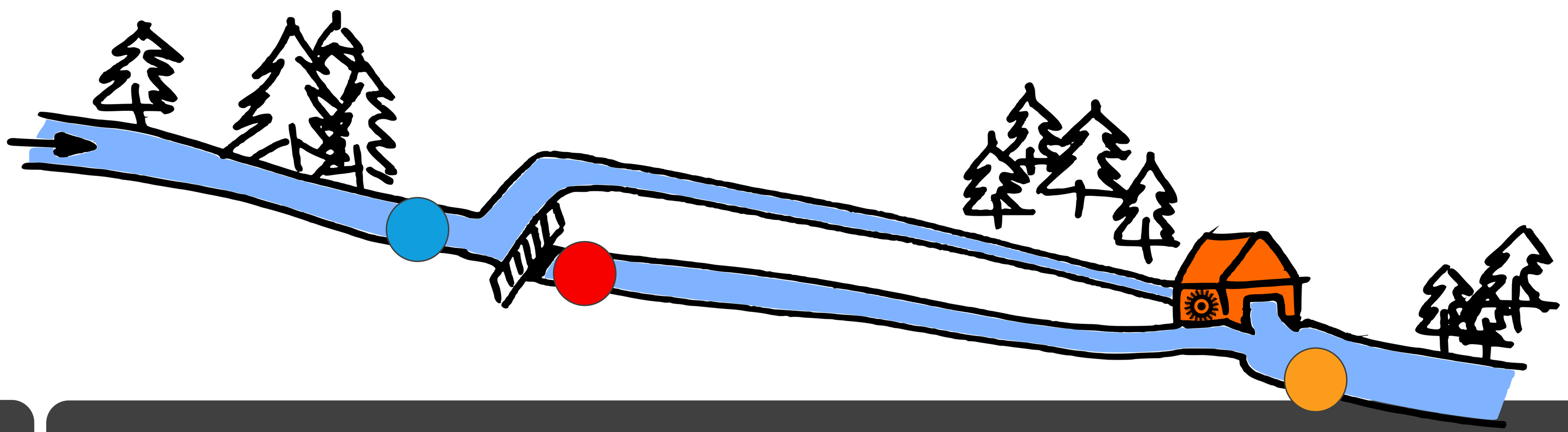
Studying seven small-scale run-of-river hydropower plants (< 3MW)

Small-scale hydropower plants are perceived to have a small ecological impact but studies assessing their local impacts are rare. A better process-based understanding is needed for designing efficient mitigation measures.

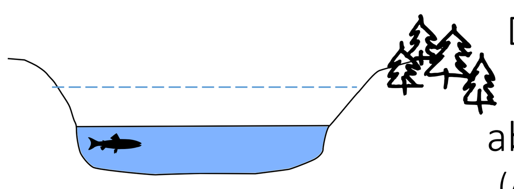


Objective

Systematic evaluation of changes in habitat conditions (habitat size, habitat stability and resources for lower trophic levels), invertebrate and fish communities among the three river reaches.

Hypotheses

Habitat size

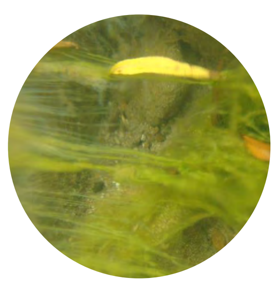


Discharge reduced from point of abstraction to return (Anderson et al. 2014).

Habitat stability

Diversion weir traps sediments -> more stable conditions downstream (Anderson et al. 2014).

Resources for algal production

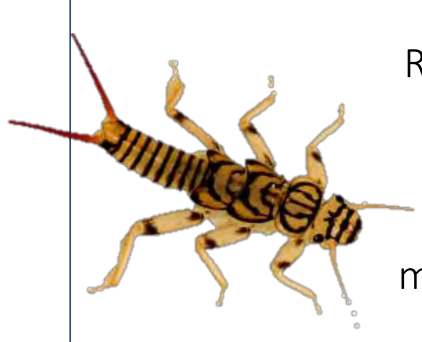


Differences in flow velocity alter nutrient uptake rates -> lower nitrate concentrations (von Schiller et al. 2016).

Resources for heterotrophs

Water diversion reduces organic matter retention -> lower fine particulate organic matter concentrations (Arroita et al. 2015).

Sensitive invertebrate taxa

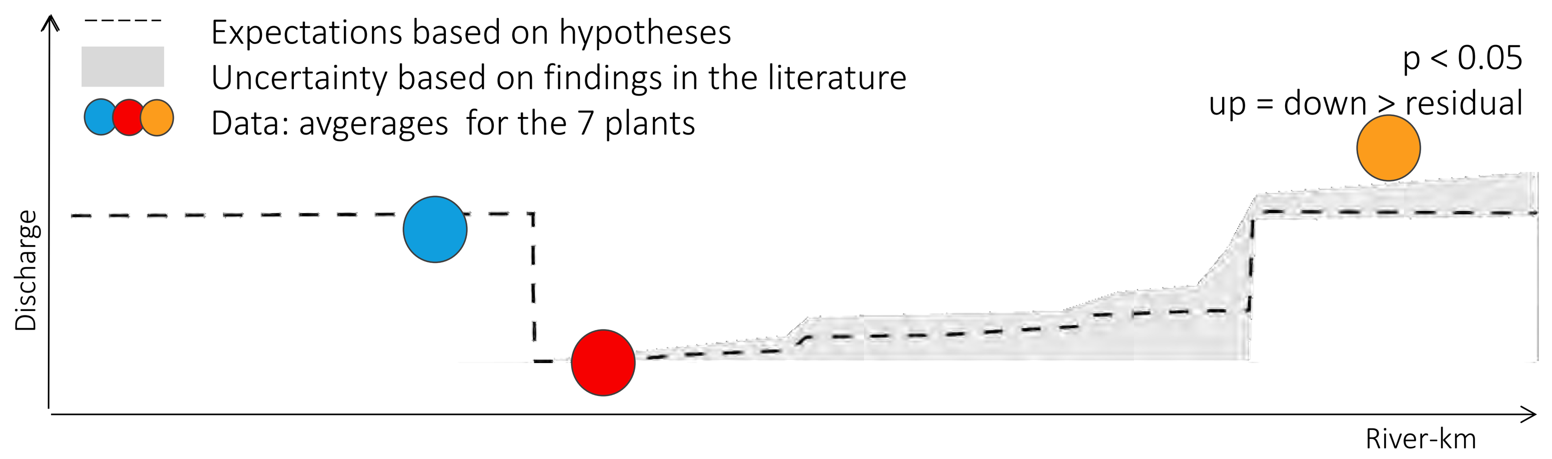


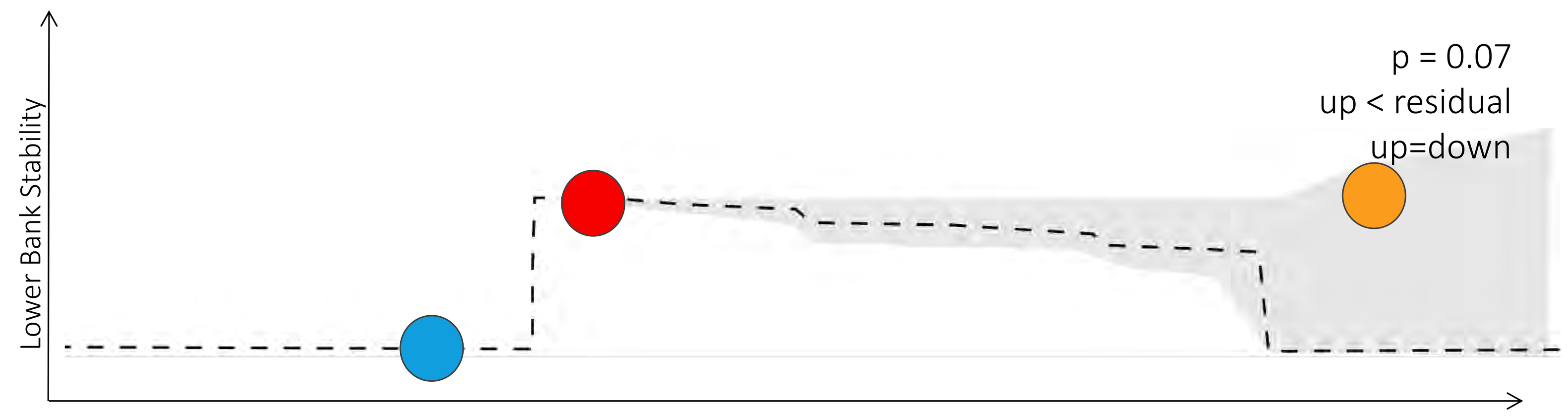
Reduced habitat size, sediment dynamics and an altered resource supply reduce the proportion of the sensitive mayfly, stonefly & caddisfly taxa (Anderson et al. 2014).

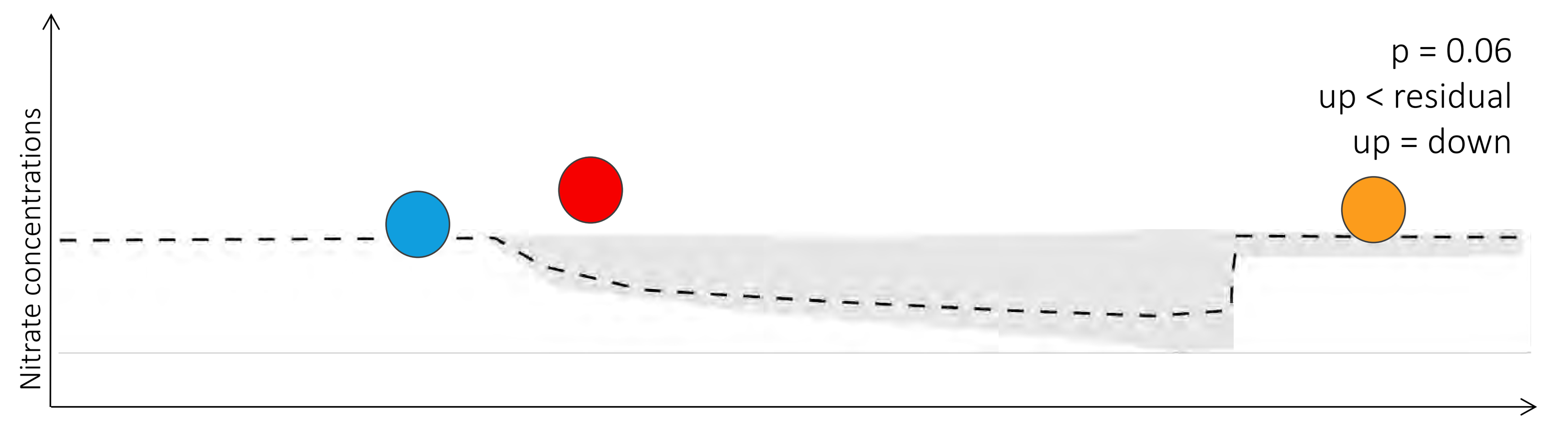
Trout somatic condition

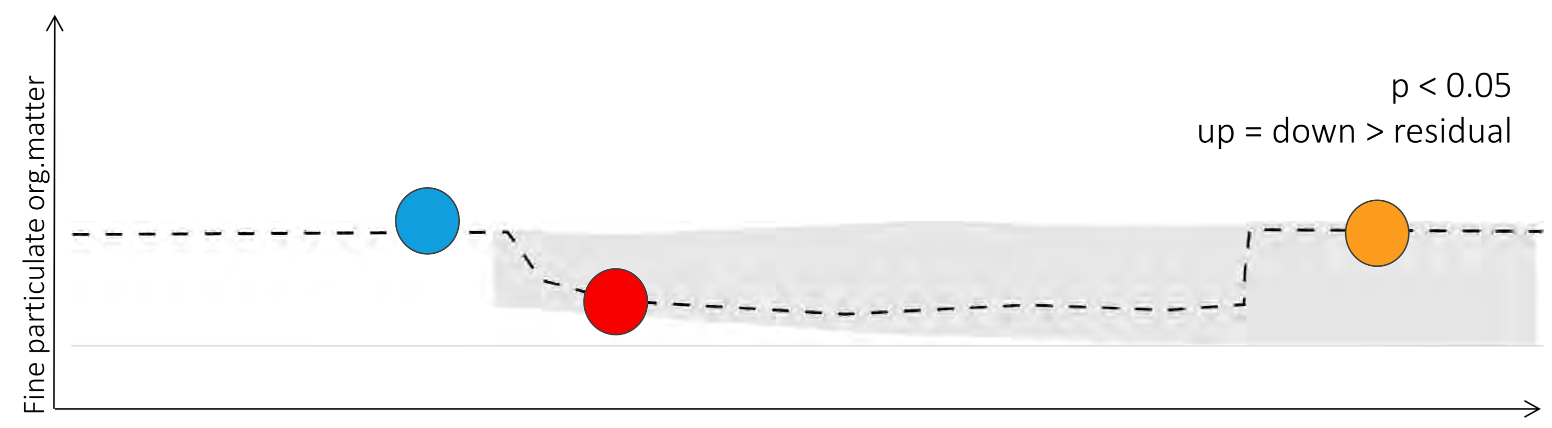
Reduced habitat availability and altered food supply will adversely affect trout somatic condition (Benejam et al. 2015).

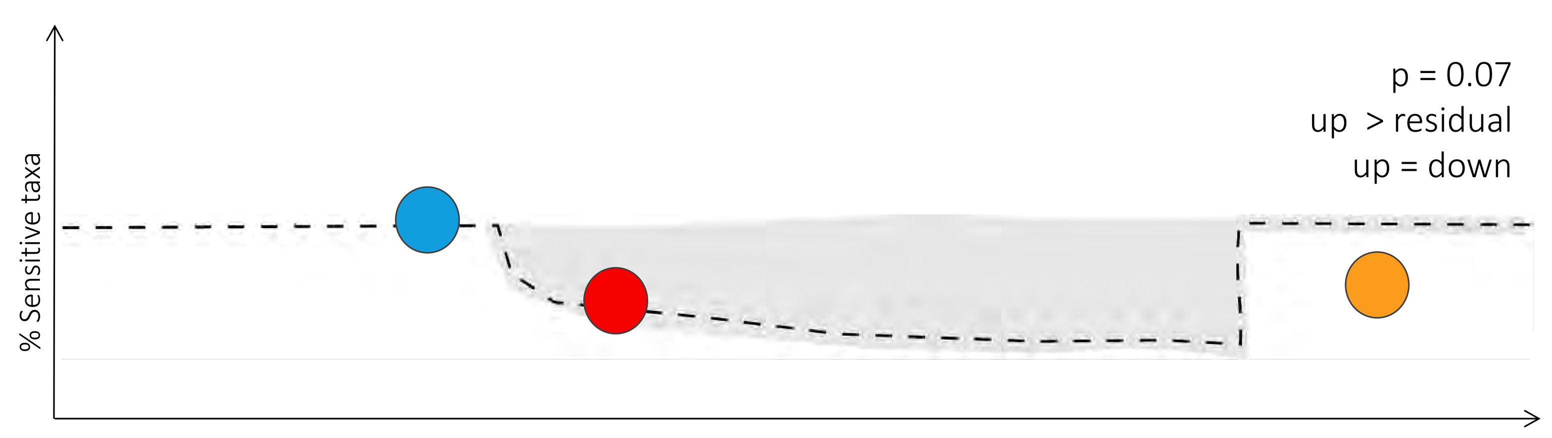
Schematic expectations (---; incl uncertainty) and results (circles)

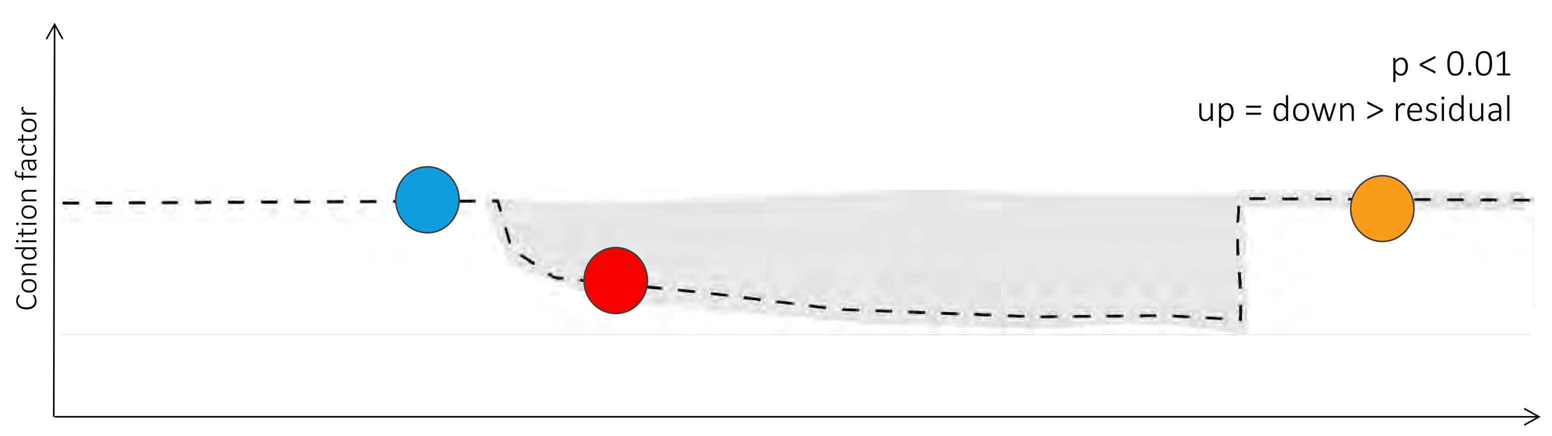


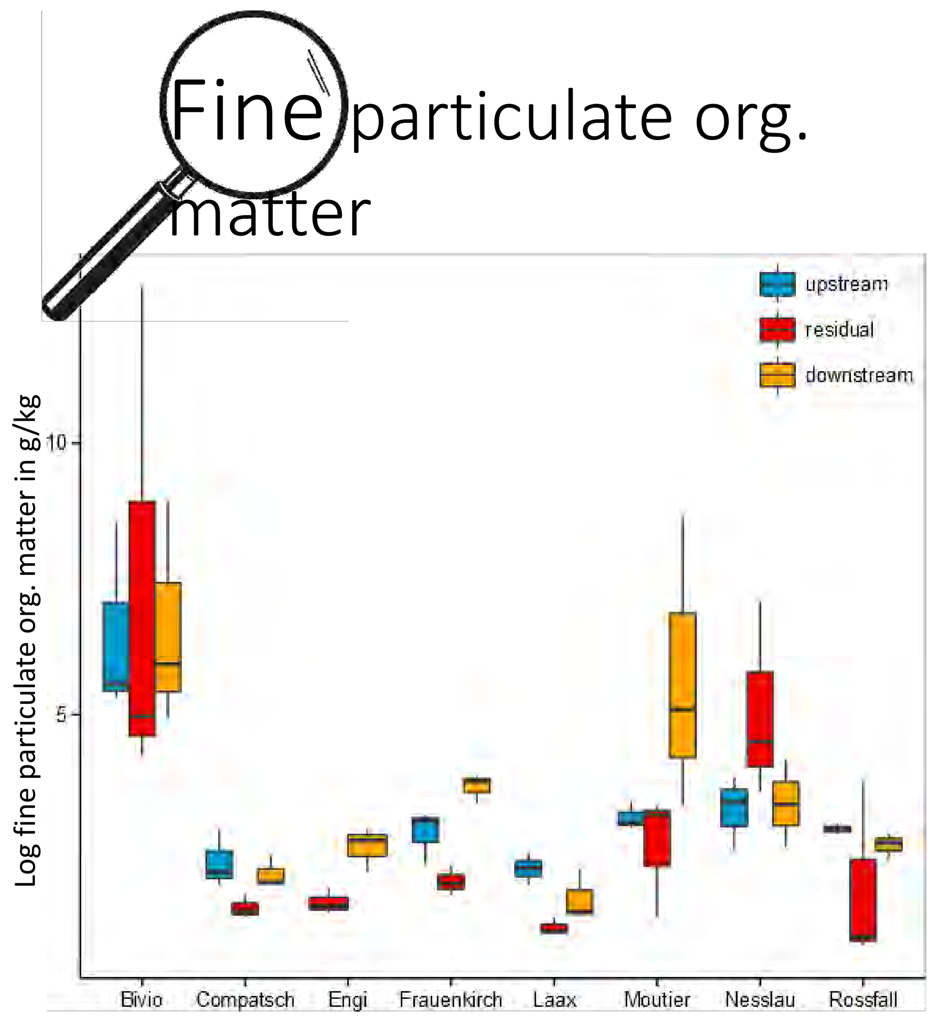


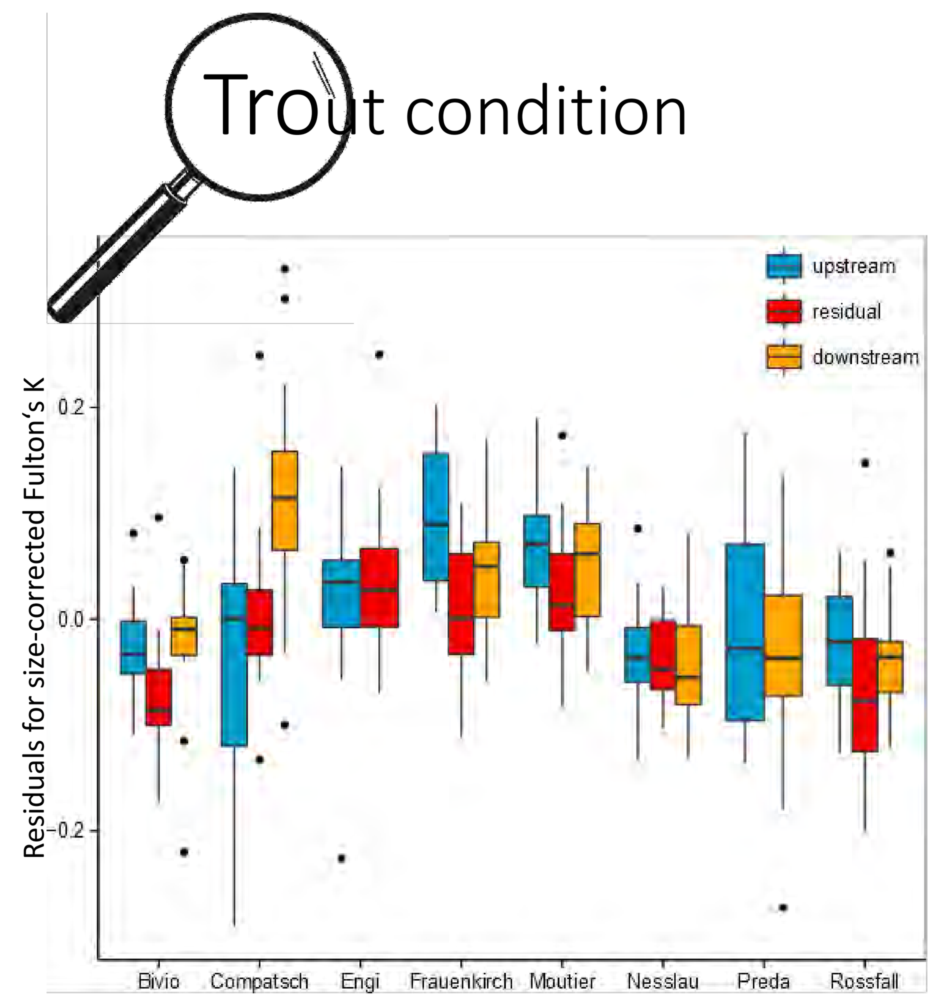












Conclusions

Small-scale hydropower plants reduced discharge and sediment dynamics which has led to more stable conditions in the residual flow reaches . This had consequences for the supply of resources for algal and invertebrate communities which may have then reduced the proportion of sensitive invertebrate taxa and trout condition.

Outlook

Trout body condition may be reduced due to harsher habitat conditions, increased intraspecific competition or an altered invertebrate food supply. Therefore we aim to determine which variables are driving this decline. Further, we will be investigating changes ecosystem functions such as shifts in carbon resources and food-web architecture.

References

Anderson et al. (2014) The impacts of 'run-of-river' hydropower on the physical and ecological condition of rivers. Water and Environment Journal, 29, 268–276.

Arroita et al. (2015) Impact of water abstraction on storage and breakdown of coarse organic matter in mountain streams. Science of the Total Environment, 503–504, 233-240.

Benejam et al. (2014) Ecological impacts of small hydropower plants on headwater stream fish: from individual to community effects. Ecology of Freshwater Fish, 25, 295–306.

von Schiller et al. (2016) Regulation causes nitrogen cycling discontinuities in Mediterranean rivers. Science of the Total Environment, 540, 168-177.

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Assessing the impacts of a pumped-storage operation on lake stratification

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Motivation

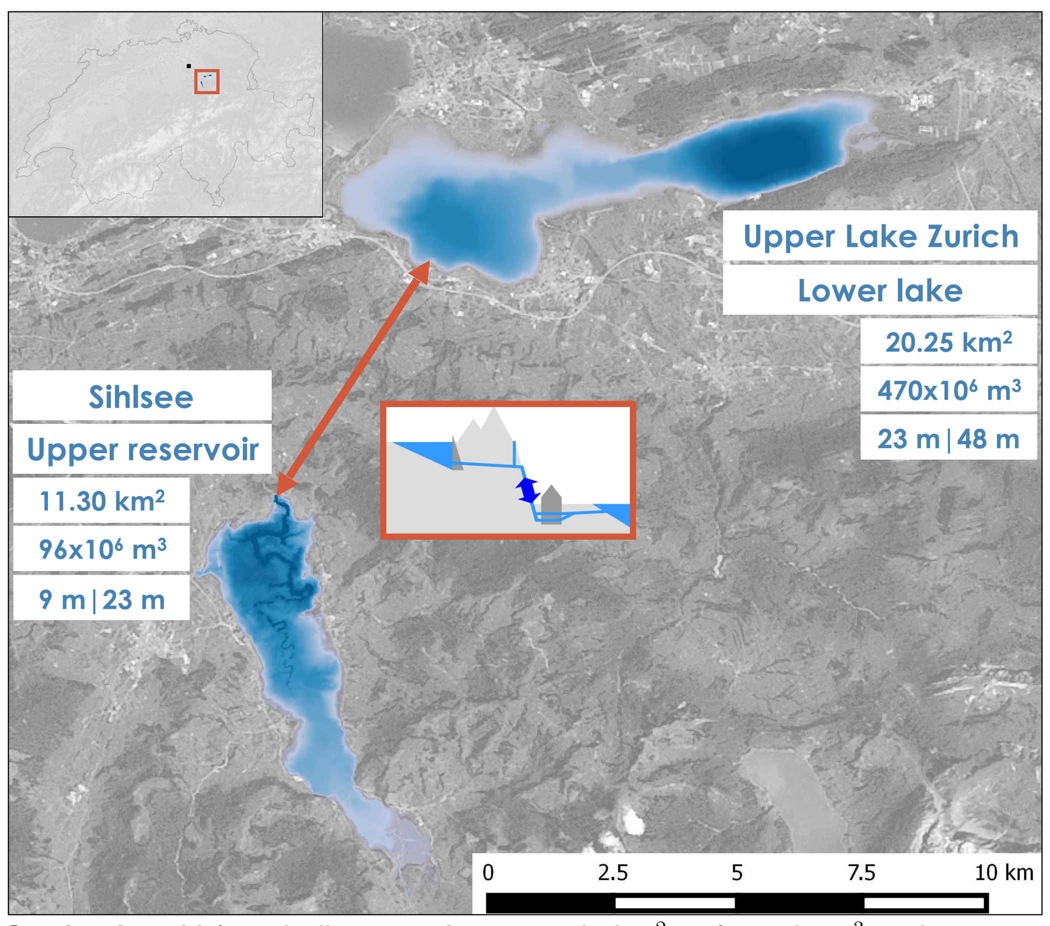
Pumped-storage hydropower plants are considered to be an important component of the future energy system in Europe for storing intermittent renewable electricity. If they involve natural lakes as storage reservoirs, the effects of pumped-storage operations (i.e. Bonalumi et al. (2011)) on the physical properties of these lakes, such as temperature, stratification and ice cover, as well as water quality, need to be limited to an extent that lake ecology is not seriously affected (GSchV (1998)).
These effects are quantified at the example of a pumped-storage hydropower plant between Sihlsee (upper reservoir) and Upper Lake Zurich (lower lake) in Switzerland.

Research Questions

What is the impact on ...

... water level fluctuations at the upper reservoir?
... water temperature of both water bodies?

Study Site



Study site - Values indicate surface area in km^2, volume in m^3 and average and maximum depth in m of the upper reservoir (Sihlsee) and the lower lake (Upper Lake Zurich)

Discussion & Conclusions

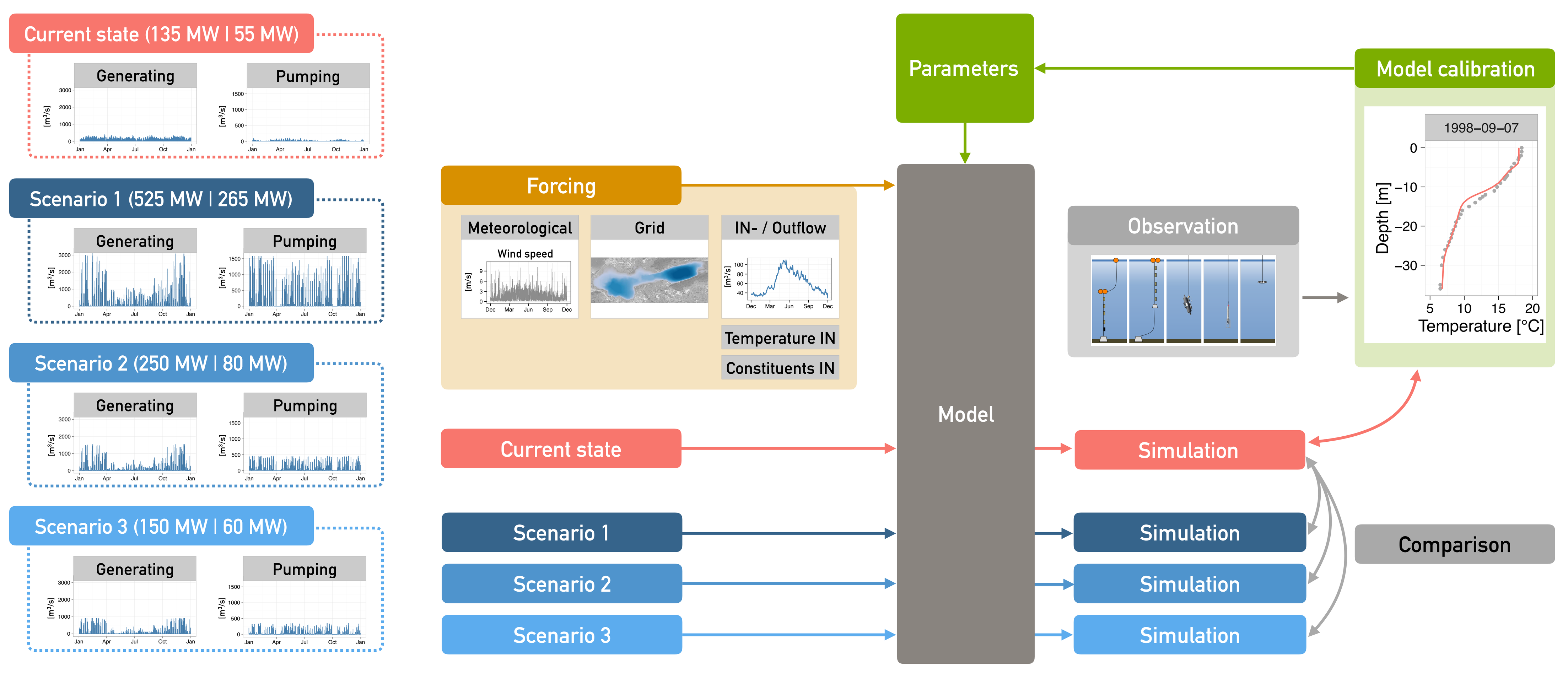
Water level fluctuations

The water level fluctuations of scenario 1 and the current state differ not only during summer due to pumping and the short term fluctuations being introduced, but also in winter where pumping leads to refilling the upper reservoir from a lower to an upper limit allowed by policy at the shortest time scale of $\approx$ 20 days.

Water temperature

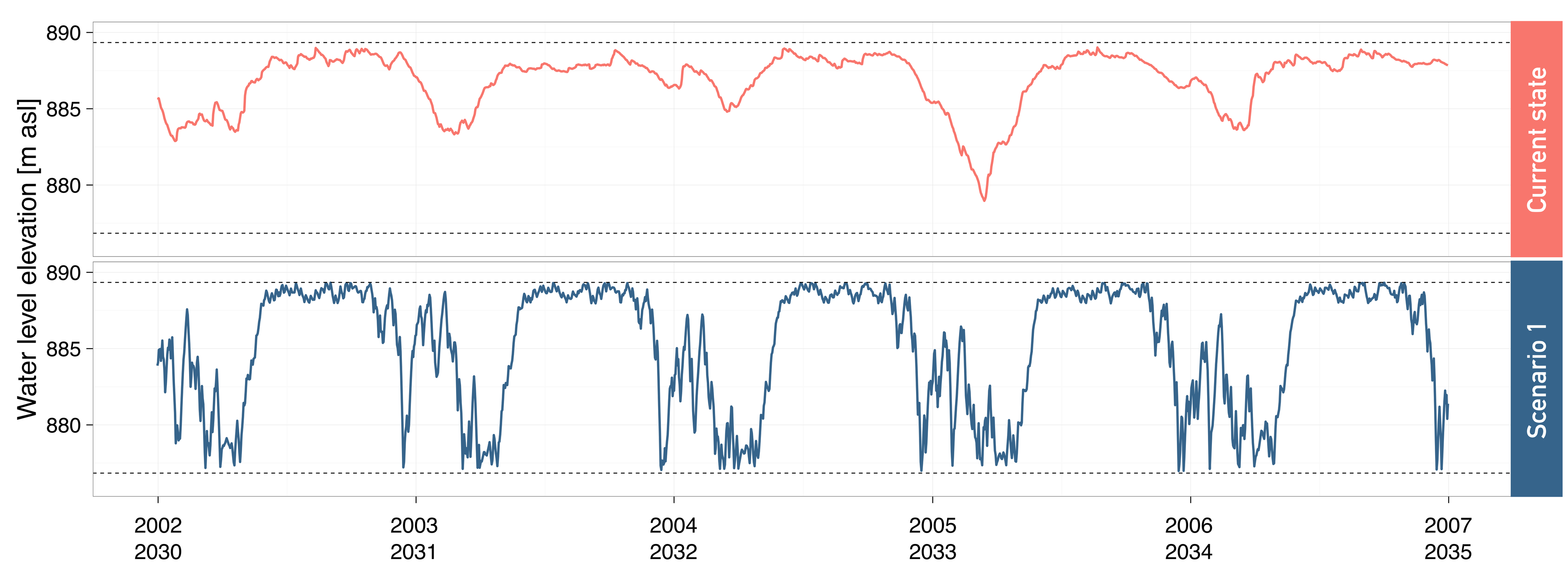
Scenario 1 would increase the hypolimnion temperature of the upper reservoir by about 2°C in summer. For winter the overall median of the water temperature would increase by 0.5°C. At the lower lake water temperature would change for both February and August less than 0.5°C.
Summer temperature increase at the upper reservoir is mostly related to introducing surface water from the lower lake to the hypolimnion.

Methods



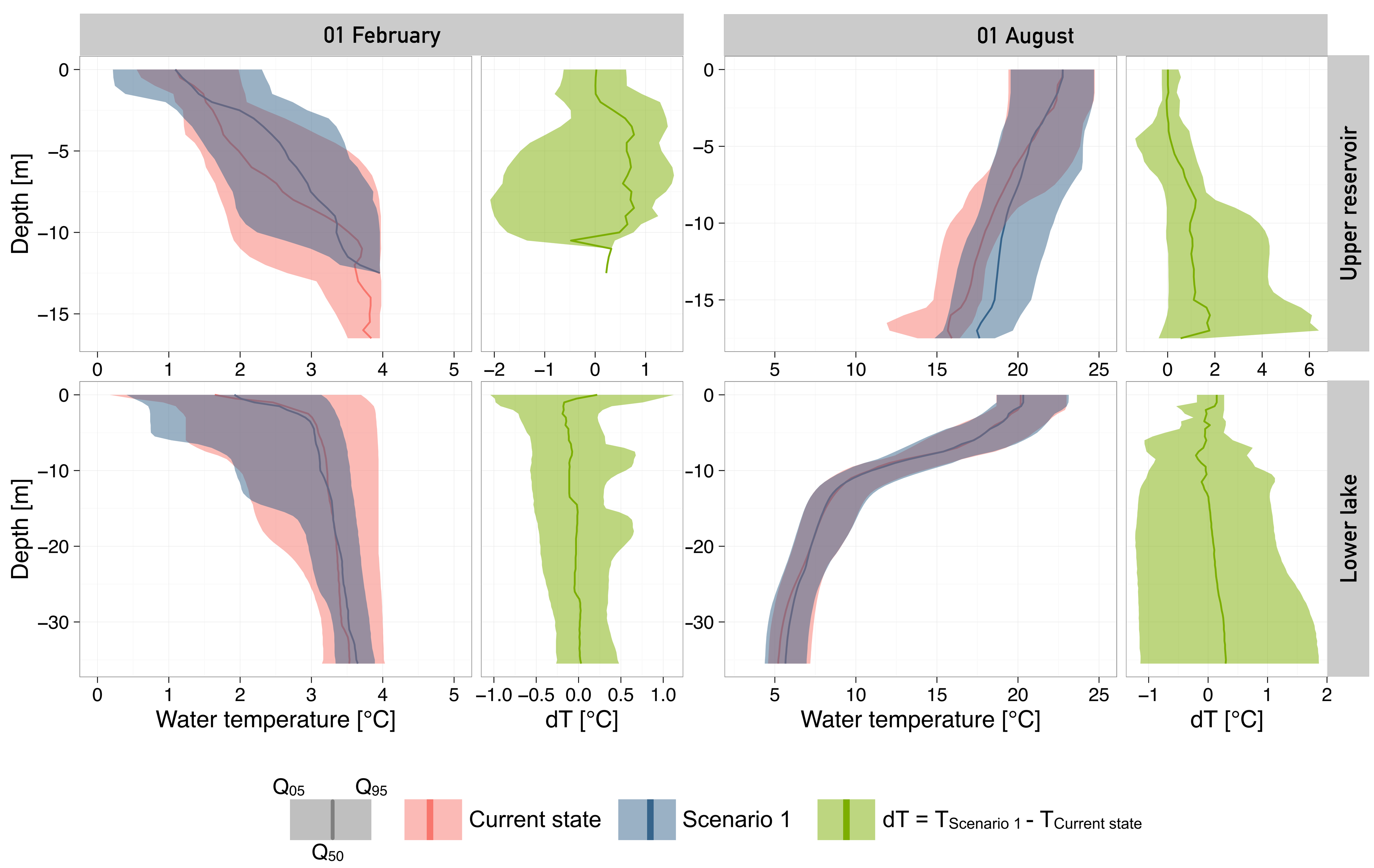
Results

Water level fluctuations - Upper reservoir



Water level fluctuations - comparison of current state and scenario 1

Water temperature



Water temperature - Median (Q_{50}), 5%- and 95%-quantiles (Q_{05}/Q_{95}) of simulated temperature profiles on 01 February and 01 August for 16 years comparing current state (1997-2012) and scenario 1 (2025-2040) as well as their differences

References

Bonalumi, M., Anselmetti, F., Kaegi, R., and Wüest, A. (2011). Particle dynamics in high-Alpine proglacial reservoirs modified by pumped-storage operation. *Water Resources Research*, 47, W09523.
GSchV (1998). Gewässerschutzverordnung (SR 814.201).

Acknowledgments

We thank A. Wüest for his overall advice, P. Meier for his suggestions concerning model calibration, P. Kathriner, M. Schurter and M. Plüss for laboratory and field assistance, the staff at Etzelwerk for their support with field work, the Swiss Federal Railways for funding this thesis as well as the following institutions for providing data - MeteoSwiss, SC Sihlsee, FOEN, cantonal agencies (St.Gallen, Schwyz), WSL and WVZ.

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Hydro-peaking mitigation measures: performance of a complex compensation basin considering future system extensions

Philipp Meier[1], Martin Bieri[2], Pedro Manso[2], Steffen Schweizer[3], Andres Fankhauser[3], and Benno Schwegler[3]

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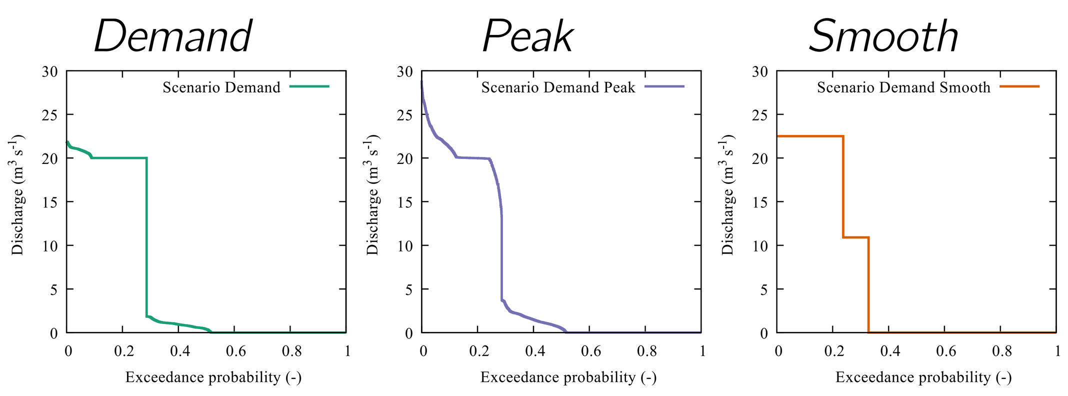
Introduction

Many Alpine rivers are affected by hydro-peaking, strong sub-daily fluctuations of discharge caused by intermittent power production from hydropower plants. Adding a retention volume at the outlet of a hydropower plant aims at attenuating hydro-peaking to a level where adverse effects on fish and invertebrates are minimal. The performance of such a retention volume needs to be assessed when extensions to the hydropower system are envisaged to improve operational flexibility.

Methods

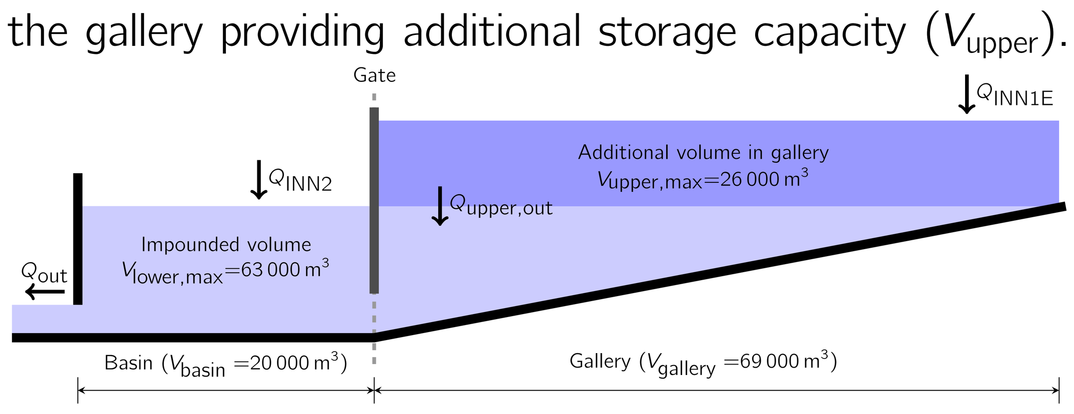
Discharge scenarios

The retention basin is at the outlet of a complex hydropower system. It would be impractical to model the whole system. The assessment therefore relies on discharge scenarios for future inflows.
Three scenarios for INN2:



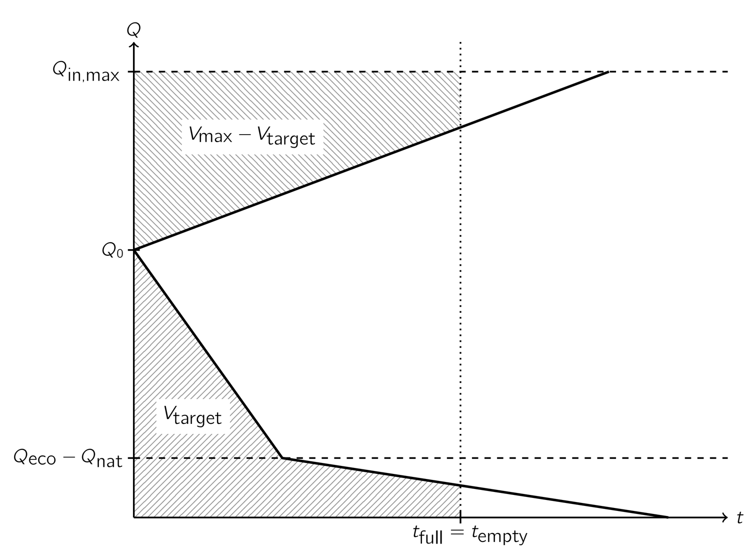
Basin operation model

The gallery and the basin are connected through a gate, making their operation interdependent. If the gate is open, the water level in the gallery is the same as in the basin. Therefore, the basin and the lower part of the gallery are operated as one single volume (V_{lower}). Closing the gate allows for a higher water level in the gallery providing additional storage capacity (V_{upper}).



A rolling horizon optimisation model that takes a decision at every time step based on the system state and information about future inflow is established.
The basin discharge Q and gradients J are controlled by the optimisation algorithm, maximising future flexibility at the end of the planning horizon by defining a target volume (V_{target}).

$$\min_{Q_{out}(t)} \left(\frac{V_{lower}(t_{end})+V_{upper}(t_{end})-V_{target}}{V_{lower,max}+V_{upper,max}}\right)^2 + \sum_t \left(f_{neg}(J,t)\, f_{low\ flow}(Q,t)+f_{pos}(J,t)\right)$$



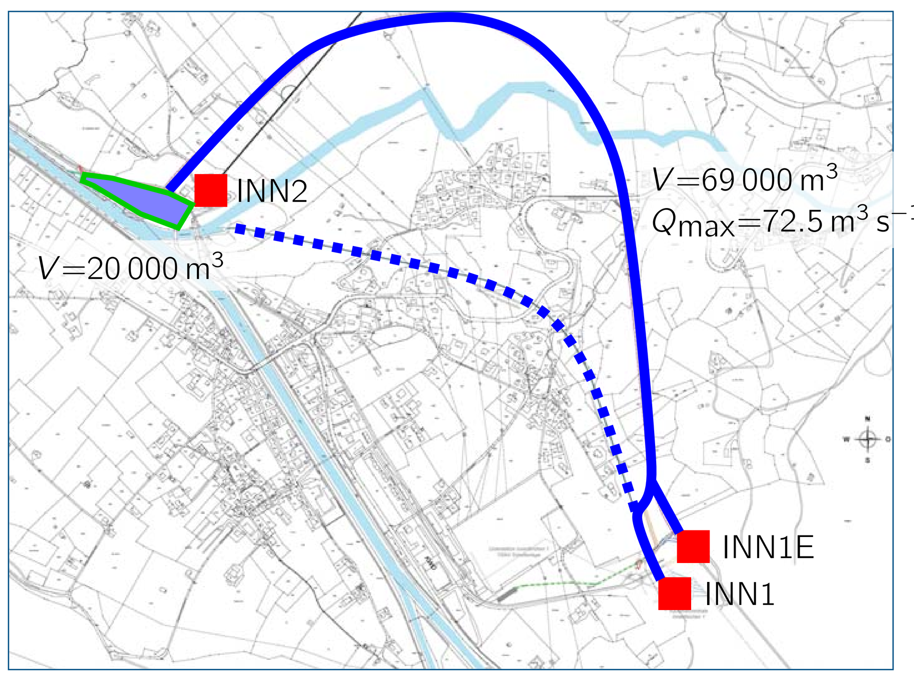
Two possible planing horizons are evaluated. A horizon of **30 minutes**, as it is current practice and a horizon of **45 minutes**.

Case study: the KWO system

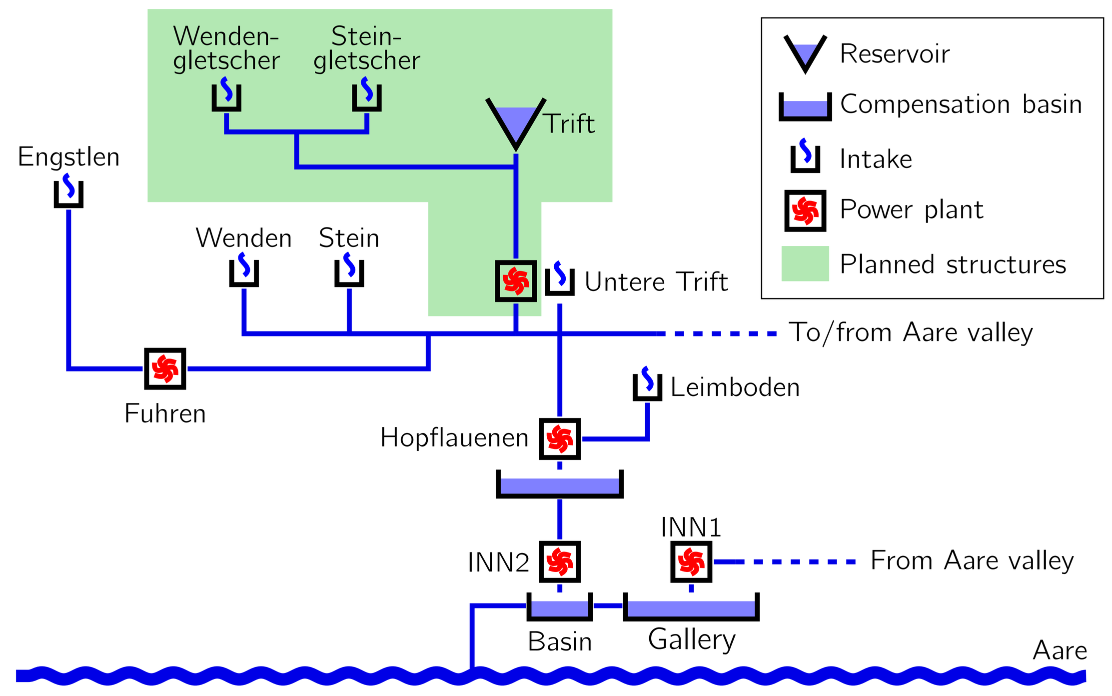
The KWO system is located upstream of Lake Brienz in the canton of Berne in Switzerland. Electricity is produced along a cascade of reservoirs and power plants. The most downstream power house, Innertkirchen 1 (INN1), returns the water to the Aare river. Within the eastern tributary valley of the Gadmerwasser river no storage is available, but several run-of-river power plants are installed in a cascade and water is returned the Aare river through the Innertkirchen 2 (INN2) power plant.

Retention basin

To mitigate hydro-peaking caused by the two power plants INN1 and INN2, a retention volume was constructed and commissioned in summer 2016. Due to space constraints, the volume was built partly as an underground gallery and an open-air basin. The retention volume is actively operated.



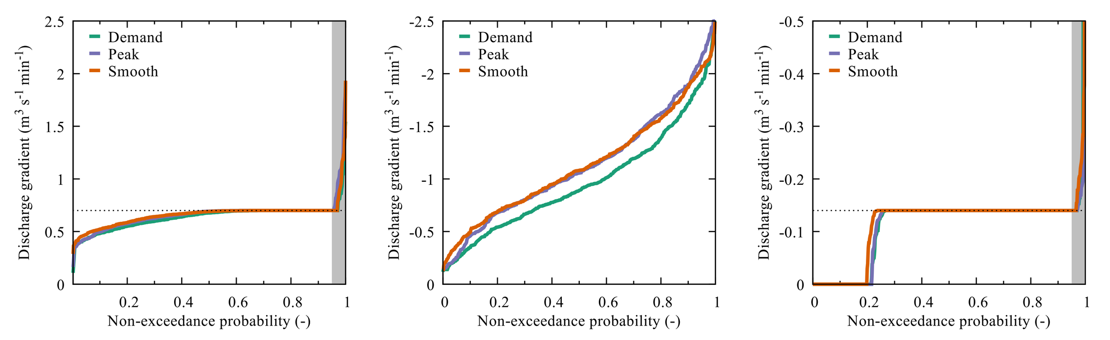
Trift reservoir



The addition of the Trift reservoir will add storage to the Gadmerwasser system, now operated as run-of-river. A new power plant will be built at the location of the existing water intake at Untere Trift. This power plant will have an installed capacity of 80 MW and a design flow of 20 m^3 s^{-1}.

Results

30 minutes lead time

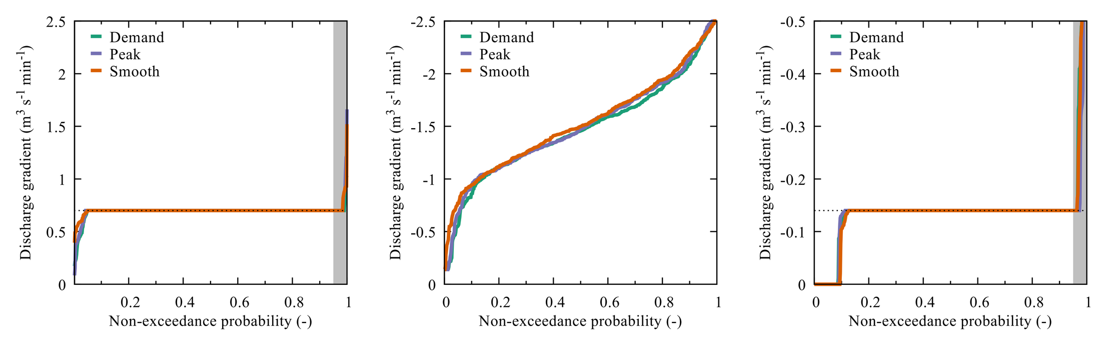


✓ hydro-peaking limit is **not violated** on more than 5% of all days (grey shaded area).

- positive gradient limit not reached on 50% of days
- negative gradient limit reached at 70% of all days

➜ Some headroom left for more extreme inflows or better operation.

45 minutes lead time



✓ hydro-peaking limit is **not violated** on more than 5% of all days (grey shaded area).

- positive gradient limit reached most of the time
- negative gradient limit reached more often

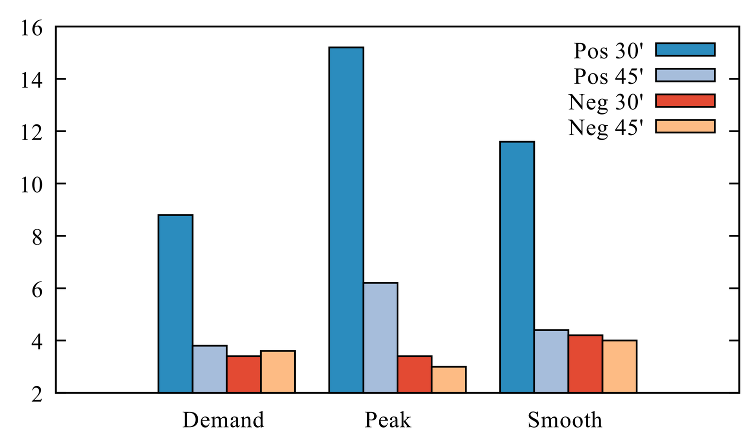
➜ Longer lead time translates to more extreme operation.

Reduction of gradient violations due to longer lead time

✓ Positive gradient violations significantly reduced

✗ No effect on negative gradients during low flows

➜ Limited operational flexibility during low flows because of the large volume of water needed to comply with gradient threshold.



Hydro-peaking targets

- Main goal is the reduction of the **rate** at which the **water level increases or recedes**.
- gradient limits apply during winter, from November 20 to March 10
- Reduce drift of invertebrates and fish
  - positive discharge gradients limited to 0.7 m^3 s^{-1} min^{-1}
- Reduce risk of stranding fish
  - negative gradients limited to -0.14 m^3 s^{-1} min^{-1} during low flows, smaller than 8.1 m^3 s^{-1}
- gradient limits cannot be exceeded on more than 5% of days during the relevant period
- Global limit of $\pm$2.5 m^3 s^{-1} min^{-1}

Conclusions

- Scenarios used as input for optimisation model anticipating best possible operation of the retention basin after adding a new reservoir to the system.
- Optimisation maximises future flexibility.
- Basin is able to attenuate hydro-peaking respecting defined thresholds under all future scenarios.
- Longer lead time reduces the number of gradient threshold violations.

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Quantifying Weighted Usable Area Produced by Macro Roughness Elements in River Flow and Habitat Simulations

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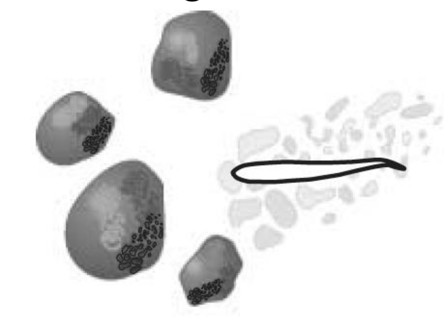
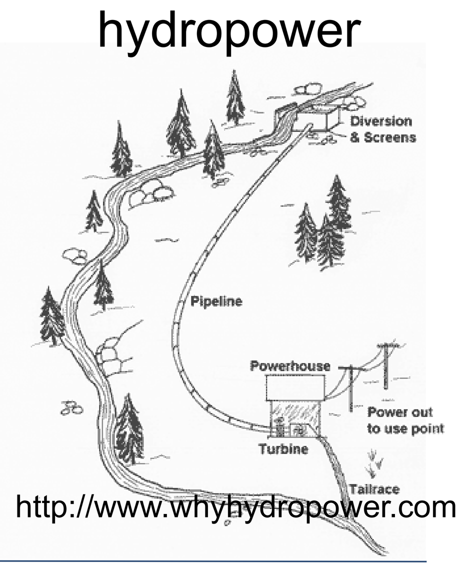
Abstract: The practice of impounding water from mountain streams for anthropogenic (e.g., hydropower) uses has been shown to significantly affect riverine ecosystem, mainly by reducing the biodiversity. The biogeomorphological basis responsible for such an effect has been related to the establishment of minimum flow requirements from river intakes and/or reservoirs (Arthington et al., 2006). To minimize this ecological impact, it is imperative to assess the extent of ecological disturbance resulted from changing the natural flow regime. The environmental suitability of flow release rules is often assessed for different species by modeling software such as CASiMir and PHABSIM (Maddock, 1999, Milhous et al., 1989). These softwares are commonly used to model Weighted Usable Area (WUA) curves for the fishes. Although they can model the WUA curves corresponding to the riverine ecosystem in large scales, they are not able to capture the hydrodynamic impacts resulted from smaller scales such as the effect of macroroughnesses (i.e., boulders). Due to the limitation of computational cost, mesh scale used in the numerical software is larger than the macroroughness size. As a result, the presence of macroroughnesses is filtered and their effect cannot be seen in the simulated WUA curves. However, the presence of stones may positively affect the riverine ecosystem by inducing sheltered zones (i.e., the wake), which are typically temporary stationary points for many fish species. Fishes minimize energy expenditure by resting in these low velocity regions, but can quickly move to nearby fast water to feed (Hayes and Jowett, 1994). By quantifying these wake areas we will be able to assess how the physical properties and number of such zones may change in response to the changing hydrologic regime. Up to a given flow rate that covers such stones, the total wake area in the river reach being monitored is therefore a function of the streamflow, Q, and it is an actual Usable Area for fishes that can be used to correct the one computed by classic software such as PHABSIM or CASIMIR at each flow rate.

Sheltering and resting



Adapted from Liao (2007)

Stream diversion for hydropower



http://www.whyhydropower.com

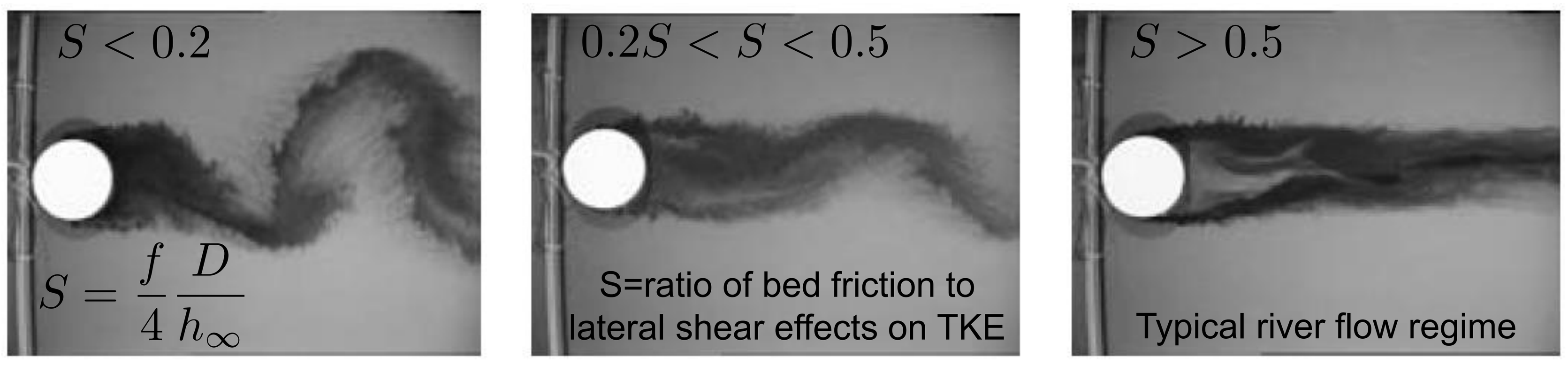
A. Project Methods

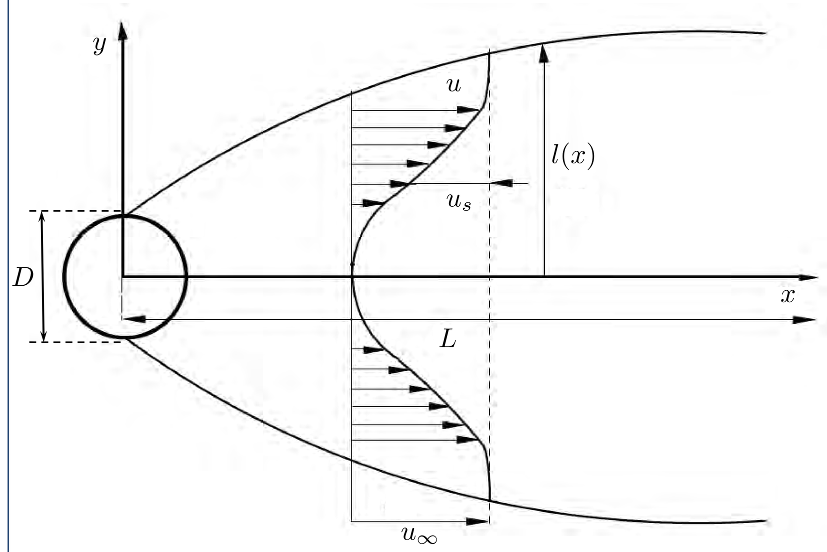
1. Survey a river using high-resolution aerial photography: Geomorphology, distribution and size of boulders

2. Use a hydrodynamic model to 2D flow conditions on a coarse grid: u_∞ and h_∞ upstream of boulders

3. Estimate the wake area behind stones:

- Use the analytical solution of the shallow water equations by Negretti et al. (2006) for wakes behind cylinders in shallow flow





For S > 0.5, obtain wake dimensions:

$$L = \frac{8h_\infty}{f} \qquad x_L = x/L$$

$$l_D = \frac{l}{D} = \sqrt{\frac{[1-\exp(x_L)]}{8S}}$$

Then integrate to estimate wake area

Adapted from Negretti et al. (2006)

4. Calculate an improved UWA estimate: Combine wake area into UWA obtained from a river habitat simulation

B. Results for a Synthetic River with 10 Boulders

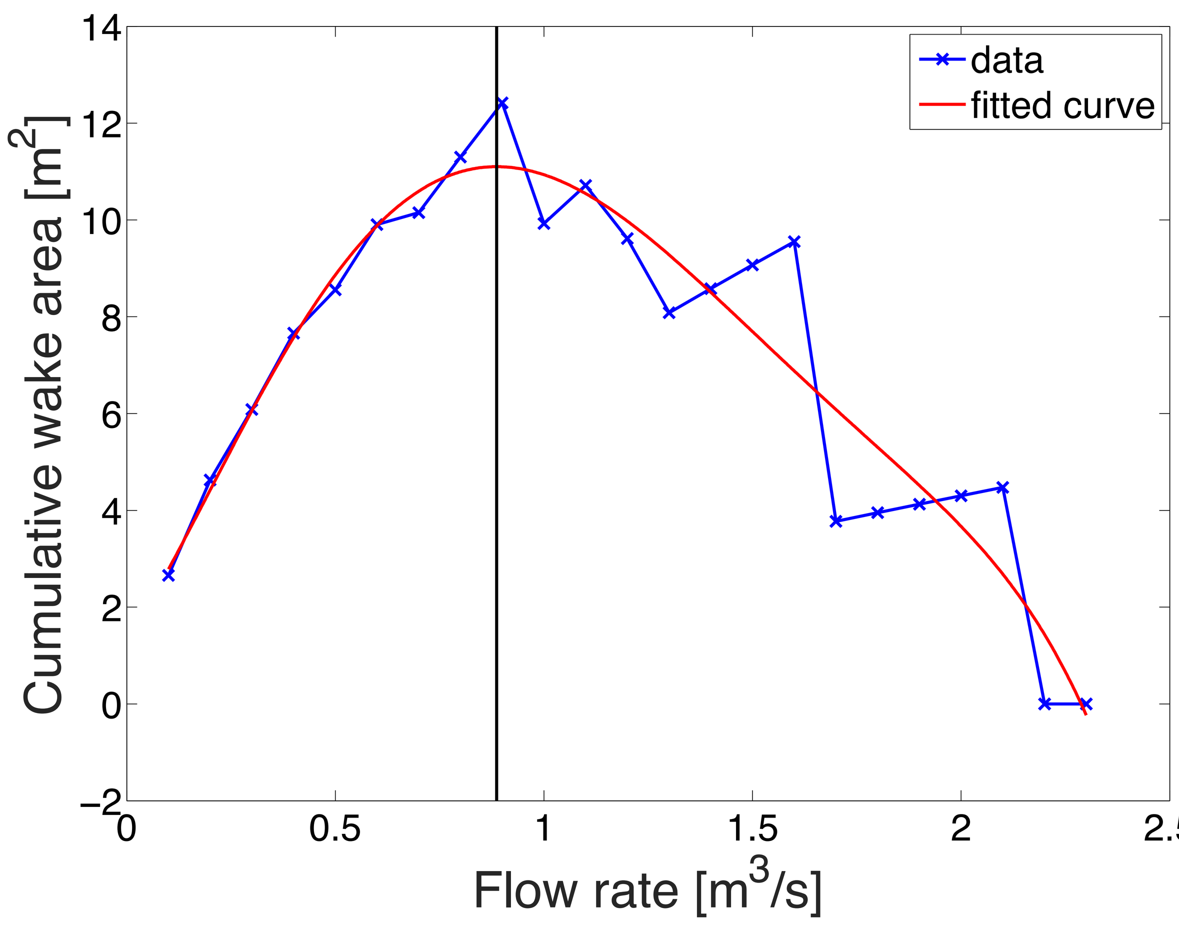
- Uniform river flow:

Q from 0 to 2.5 m^3/s

Manning coefficient: n = 1/30

- 10 boulders with random D and h:

0.1 m < D < 0.4 m
0.05 m < h < 0.25 m



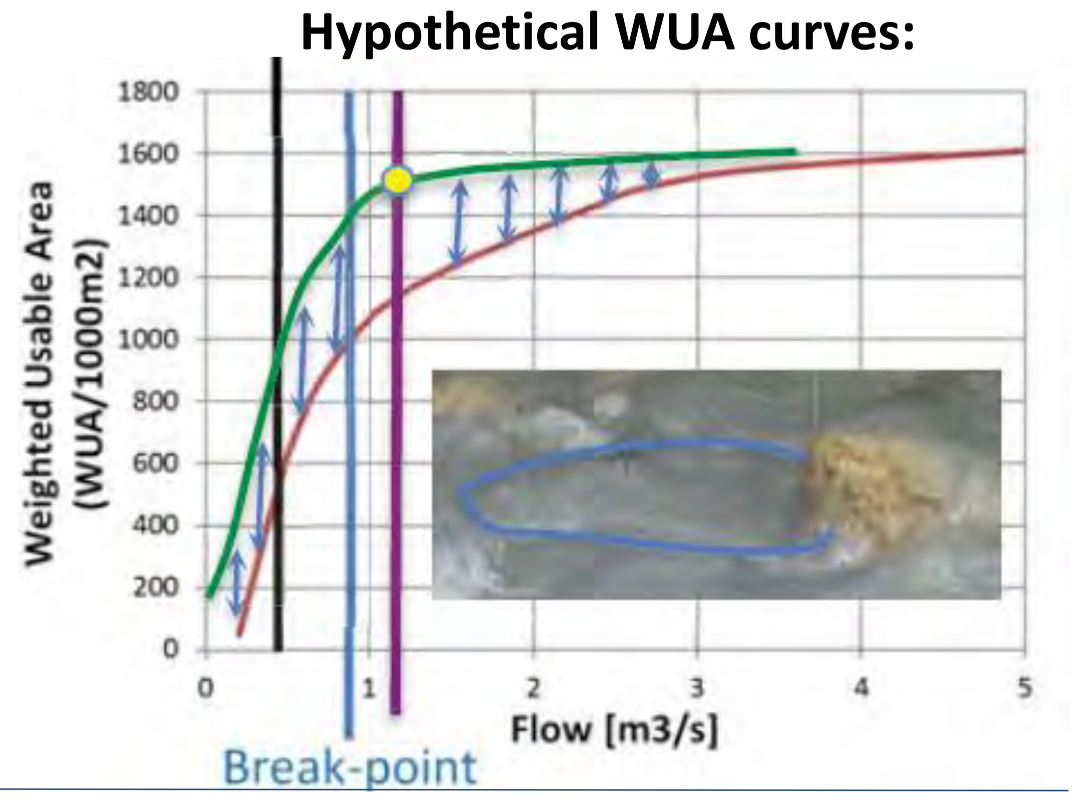
C. Implementation to Correct Traditional WUA curves

Directly incorporating the wake areas generated by boulders into WUA estimates will:

- change the curvature of the WUA estimate (from red to green lines),
- shift the threshold point (yellow dot) to the right,
- will enable lower minimum flow requirements, and result in higher potential for hydropower production.

Hypothetical WUA curves:

Note: Minimum flow requirements are typically set by a variety standards according to the UWA curves (e.g., the threshold [yellow dot] or break point [blue line]).



D. Future Work

- Perform controlled laboratory experiments to quantify uncertainties in using the Negtretti et al. (2006) solution for more realistic macro roughness elements of varying aspect ratio and shape
- Obtain field data: Ariel photogrammetry and discharge for a test river
- Test and compare our method to traditional habitat simulations, i.e., test our hypothesis.

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