Task 2.3

Title

Environmental impacts of future operating conditions

Projects (presented on the following pages)

Hydropower and water temperature: modelling the effects of management scenarios on river thermal heterogeneity
Davide Vanzo, Martin Schmid, Christine Weber and Michael Döring

Impact assessment of hydropower generation on the acoustics and visual appearance of waterfalls
Gabriel Zehnder

Coupled effect of pumped-storage operation and climate change on temperature and water quality
Ulrike Gabriele Kobler, Alfred Wüest, Martin Schmid

How are hydropower thermal alterations affecting trout populations?
Kunio Takatsu, Martin Schmid, Davide Vanzo, Jakob Brodersen

Künstliches Hochwasser und Geschiebeschüttungen in der Saane
Severin Stähly, Anthony Maître, Christopher T. Robinson, Anton J. Schleiss

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Hydropower and water temperature:

modelling the effects of management scenarios on river thermal heterogeneity

Davide Vanzo[1], Martin Schmid[1], Christine Weber[1] and Michael Döring[2]

1. *Eawag, Swiss Federal Institute of Aquatic Science and Technology, Surface Waters - Research and Management, Kastanienbaum, Switzerland*
2. *ZHAW , Zurich University of Applied Sciences, Wädenswil, Switzerland*

Introduction

- River water temperature is a fundamental physical property of flowing waters
- It is the results of **multiple energy exchanges** involving air, flow, streambed, river morphology and vegetation (Fig. 1, Dugdale et al. 2017)
- **Alterations** of the natural thermal regime at any scale can adversely affect the river biota (e.g. Caissie 2006)
- Artificial **reservoirs** and **hydropower plants** cause thermal alterations on a broad spectrum of temporal scales, and affect longitudinal thermal gradients (e.g. Vanzo et al. 2016)
- The quantification of **lateral** thermal gradient alterations is still a challenge

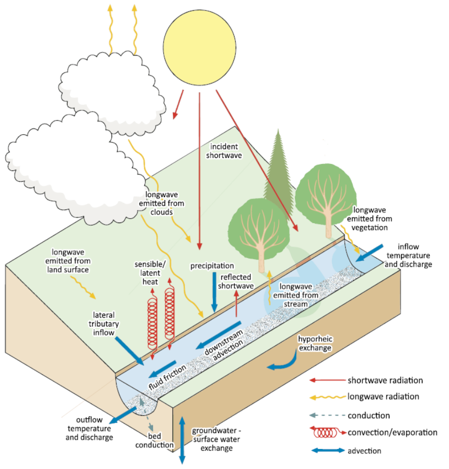


Fig. 1 - Factors influencing the thermal regime in a river reach (Dugdale et al. 2017).

Motivation

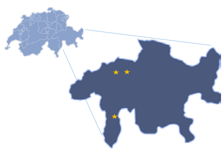
Swiss Energy Strategy 2050: changes in hydropower production patterns

- increase in storage capacity
- alternative production scheme (e.g. pump-storage)
- more frequent fluctuations of water flow (hydropeaking)

Goals

- develop a two-dimensional numerical tool for river thermo-hydrodynamics simulation
- model and quantify the interaction between hydro-thermal alterations and local river morphology
- better understand how thermal heterogeneity changes over time in hydropeaking rivers

Study sites



Canton Grigioni

3 reaches with morphological variability and subjected to hydropower production

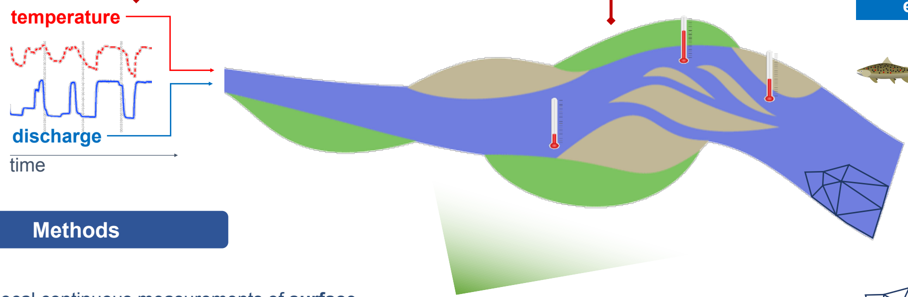
- Moesa River at Lostallo
- Rhein River (Hinterrhein) at Rhäzüns
- Rhein River (Vorderrhein) at Ilanz

Research questions

How is river **thermal regime** affected by **hydropower production**?

Does river **morphology** play a relevant role in the **thermal heterogeneity** of hydropeaking rivers?

How does river temperature affect **early life stages** of fish?



Poster: *How are hydropower thermal alterations affecting trout populations?*
Kunio Takatsu et al.

Methods

local continuous measurements of **surface** and **sub-surface** water temperature

→ to evaluate the contribution of **hyporheic fluxes** to thermal heterogeneity

remote sensing (UAV) of reach-scale surface water temperature

→ to understand thermal heterogeneity at **different flow stages** and **seasons**

development of a 2D depth-averaged **numerical model**

→ to simulate **thermo-hydrodynamics** for current and future production **scenarios**

References

Caissie, D. (2006) 'The thermal regime of rivers: A review', Freshwater Biology, 51(8)
Dugdale, S. et al. (2017) 'River temperature modelling: A review of process-based approaches and future directions', Earth-Science Reviews
Vanzo, D. et al. (2016) 'Characterization of sub-daily thermal regime in alpine rivers: Quantification of alterations induced by hydropeaking', Hydrological Processes, 30(7)

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Impact assessment of hydropower generation on the acoustics and visual appearance of waterfalls

Gabriel Zehnder, VAW (Laboratory of Hydraulics, Hydrology and Glaciology), ETH Zürich, Switzerland

Objectives

Waterfalls are some of the most impressive nature spectacles on earth. People are and have been fascinated by their appearance regardless of height or shape. Numerous historical narratives and urban histories mention waterfalls and the question of which is the highest and biggest waterfall is still ongoing. However, due to steadily rising energy demand waterfalls are becoming more and more affected by anthropogenic interventions and their impressive appearances are in danger.
These facts lead to the first two key questions:

1) How big are the impacts of hydropower generation on waterfalls in Switzerland?

2) Are the Rhine falls really the biggest falls in Europe?

In the second part of this project a case study on the energetic use of the Berschnerfall (canton of St. Gallen, CH) is performed, with the help of the power plants Walenstadt, to answer the third key question:

3) What is the most economic exploitation alternative considering the conservation of the appearance of the Berschnerfall.

Handbook for assessing the key questions

Identify energetically used waterfalls in Switzerland	Identify big (energetically used) waterfalls in Norway, Island, Switzerland	Classification of the Berschnerfall
Collect discharge data of the falls	Collect discharge data of the falls and differ between natural and exploited state	Find appropriate residual flow and discharge capacity of turbine to preserve the appearance of the falls
Classify the falls according to Plumb, Beisel, Schwick & Spichtig and VAW method	Classify the falls according to Plumb, Beisel, Schwick & Spichtig and VAW method	Find potential locations for new powerhouses below the Berschnerfall
Evaluate the impact of hydropower generation with the consequence matrix of the VAW	Comparison of natural and exploited state	Development of different modes of operation
Development of new characterization method to summarize all other methods	Determine the biggest falls	Find the best location and mode of operation to maximize the revenues

Energetically used waterfalls

22 energetically used waterfalls in Switzerland are identified (see Fig. 1). For these, only little discharge data is available. Therefore, data comparison between measured data from hydrological yearbooks and modelled data from the Federal Office for the Environment FOEN [1] is conducted for 6 reference sites with existing hydrological yearbook data (see Fig. 2). By applying an equation developed by HZP [2], the modelled data can be recalculated, achieving a sufficient accuracy with a deviation of less than 20% (red line in Fig. 2) from the measured data.

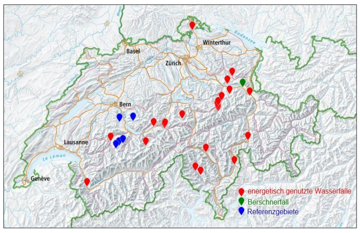

Fig. 1: Map of energetically used waterfalls in Switzerland (red), of the reference sites (blue) and the Berschnerfall (green) [1].

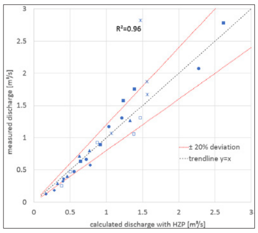

Fig. 2: Data comparison of measured and calculated discharge data.

Based on the recalculated discharge data, the classification and VAW consequence matrix (Fig. 3) is then calculated.
The data of the European waterfalls can be found on the federal sites of the corresponding countries [1],[3],[4].

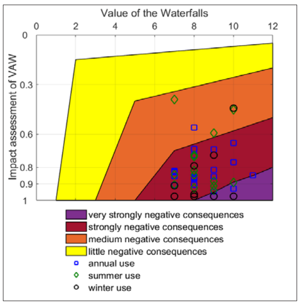

Fig. 3: VAW consequence matrix of the Swiss falls based on annual and seasonal discharge data.

	Rhine falls (CH)	Fiskumfoss (NO)	Dettifoss (IS)	Sarpsfossen (NO)
Height [m]	23	34.5	44	23
Width [m]	150	186	100	80
Q_m [m³/s] natural	340	302.4	193	662
Q_m [m³/s] used	310	185.6	0	308.7
Q_{max} [m³/s]	1250	1482	508	3000
Plumb	61.2	66.2	103.2	114.6
Beisel natural	8	7	6	7
Beisel exploited	8	7	0	6
Schwick & Spichtig	10	10	11	10
VAW consequence	0.22	0.43	0	0.67

***Table 1**: Overview of the biggest waterfalls in Europe.*

Case study - Berschnerfall

Two new locations below the Berschnerfall are proposed (Fig. 4). For every location three different residual flows are compared within four different modes of operations (daily use, only night use, day/night different use and seasonal different use). The lowest residual flow is defined by law as 53.1l/s. The remaining two options are chosen based on a minimized impact on the appearance of the fall: 120l/s (= $0.36 \cdot Q_{182d}$) and 162l/s (= $0.5 \cdot Q_{182d}$).

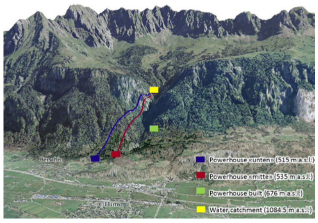

***Fig. 4**: New proposed locations of the powerhouses [1].*

	Powerhouse built	Powerhouse «unten»	Powerhouse «mitte»
Drainage tunnel length	1315 m	1751 m	1624 m
Net drop height	407.6 m	569.5 m	549.5 m
Discharge capacity	1000 l/s (= Q_{60d})	1000 l/s (= Q_{60d})	1000 l/s (= Q_{60d})
Residual flow of best mode of operation	53.1 l/s	winter 53.1 l/s, summer 162 l/s	winter 53.1 l/s, summer 162 l/s
Annual electricity production	11.20 GWh	14.35 GWh	13.45 GWh
Construction costs	21.5 million CHF	24.7 million CHF	23.8 million CHF
Production costs (internal rate 3%)	5.10 Rp/kWh	4.70 Rp/kWh	4.74 Rp/kWh
Profit after concession (80 years) (with electricity price of 5.81 Rp/kWh and internal rate of 3 %)	15.3 million CHF	19.8 million CHF	18.1 million CHF

***Table 2**: Overview of the three powerhouse options for the bestcase scenario.*

Conclusions and Perspectives

1) Waterfalls in Switzerland experience mostly strongly to very strongly negative consequences from anthropogenic interventions linked to hydropower generation.

2) The selection of the biggest waterfall depends on the perspective of the comparison:
   - Plumb = mainly dependent on geometric parameters → Sarpsfossen is the biggest
   - Beisel = focuses on water volume in the falls → Rhine falls are the biggest
   - Water discharge → Sarpsfossen is the biggest in natural conditions, whereas in exploited conditions, the Sarpsfossen and Rhine falls are leading

3) The economic and ecological best case is the case with seasonal different residual flow (53.1 l/s and 162 l/s) and with the powerhouse located in the middle.

References

[1] FOEN (2012). Geoinformationplatform of Switzerland. https://map.geo.admin.ch. Visited: 22.05.2018.
[2] Niedermayr, A. (2012). Ermittlung von Abflussdauerlinien in Einzugsgebieten ohne Abflussmessungen. Hunziker, Zarn & Partner AG, Aarau.
[3] NVE (2018). NVE Atlas. Norwegian Water Resources and Energy Directorate. https://atlas.nve.no. Visited: 22.05.2018
[4] NVE (2018). Xgeo.no – expert tool for notification and emergency. Norwegian Water Resources and Energy Directorate. http://www.xgeo.no/. Visited: 22.05.2018

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Coupled effect of pumped-storage operation and climate change on temperature and water quality

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[2] EPFL, Physics of Aquatic Systems Laboratory - Margaretha Kamprad Chair
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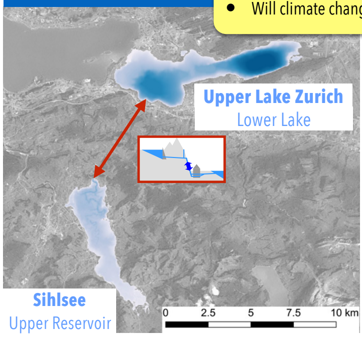
RESEARCH QUESTIONS

- How does the operation of a pumped-storage (PS) hydropower plant affect climate change impacts on lakes and reservoirs?
- Will climate change impacts be reduced by PS operation?

Study site



Introduction

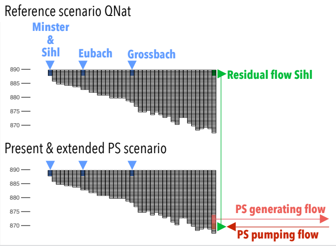
Effects of climate change on lakes and reservoirs include increasing surface water temperature, prolonged summer stratification [1, 2], decreasing duration and extent of ice cover [3, 4] as well as decreasing oxygen and increasing nutrient concentrations [5]. Additionally, climate reduction goals enhance the implementation of "new renewable" electricity production, which relies on appropriate storage capacity, that can be provided by PS hydropower plants. However, these PS operations additionally affect physical, biogeochemical and ecological properties of the connected water bodies [6].

As to our knowledge there are no studies on these coupled effects, we combine three different PS operation scenarios with two different climate scenarios to assess the impacts on temperature, stratification and dissolved oxygen at the Etzelwerk PS hydropower plant, which connects Sihlsee and Upper Lake Zurich. The climate scenarios include meteorological and inflow temperature forcing and consist of an ensemble of ten scenarios for both the current (1998-2012) and the future conditions (2078-2092). All climate scenarios were generated with a vector autoregressive weather generator [7]. The climate signal for future conditions was taken from CH2011 [8] for the A2 scenario in northeastern Switzerland in 2085.

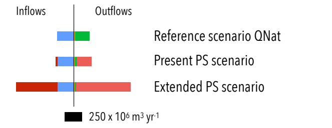
Results are aggregated to mean and minima as well as maxima from all realisations of the weather generator and all realised 15 years.

Materials and Methods

Bathymetry



Average annual water balance



Hydrological forcing

PS scenario dependent forcing [6]

PS scenario independent forcing [9]

Climate scenarios

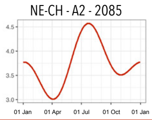
Observed variables

Current climate

$\Delta T = 0$ °C

Future climate

ΔT from CH2011 [8]
NE-CH - A2 - 2085



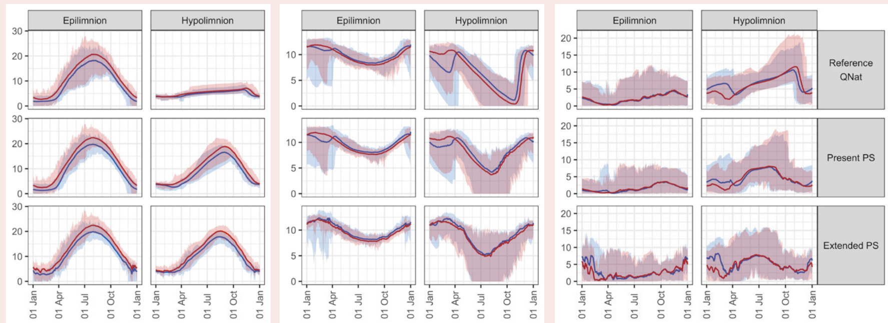
Weather generator [7]

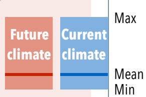
Ensemble of projected variables

T_{AIR}, T_{DEW}, u, v, Q_{SW}, Q_{LW}, T_{INFLOW}

MODEL [10]

RESULTS



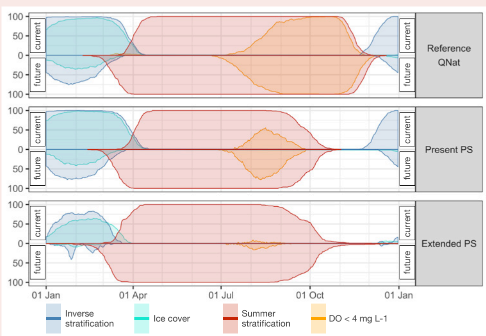


- Hypolimnion temperature differs by ~0.5, ~2.5 and ~2.4 °C for the reference, present PS and extended PS scenarios due to climate change.
- Epilimnion temperature increases due to climate change by maximal ~2.7 °C independent of PS scenario.

- Less oxygen gets dissolved in the epilimnion in future due to higher water temperature.
- Prolonged stratification results in reduced dissolved oxygen concentrations in the hypolimnion.
- In winter reduced ice cover leads to increased dissolved oxygen concentrations in both epi- and hypolimnion.

- For the "quasi-natural" reference scenario QNat prolonged stratification results in higher phosphate concentrations in fall, which is not really observed for the scenarios with PS operation.
- In winter less ice cover and consequently more mixing reduces the phosphate concentrations especially in the hypolimnion.

Probability [%]



- Inverse stratification is reduced and ice cover could even diminish due to the combination of extended PS operation and climate change.
- Although the duration of summer stratification remains unchanged for the reference scenario QNat under current climate conditions and the extended PS scenario under future climate conditions, the timing changes, which could accordingly affect lake ecology.

CONCLUSIONS

- Temperature of the hypolimnion is strongly increased due to the pumped-storage operations. This effect is further enhanced by climate change.
- In the natural state, hypolimnetic temperatures are only slightly affected by climate change, as long as a lake remains cold enough to mix completely in winter.
- The warming of the epilimnion by climate change increases the stability and prolongs the duration of stratification.
- As a consequence of longer stratification, dissolved oxygen concentrations are lower and phosphate concentrations higher in fall. This effect is stronger in the natural state than in the PS scenarios.
- In winter, the shorter ice cover duration causes increased dissolved oxygen and decreased phosphate concentrations.
- Since concessions for hydropower are often issued for durations of 50 to 80 years, the environmental impact assessment should also consider possible effects from expected climate change.

References

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How are hydropower thermal alterations affecting trout populations?

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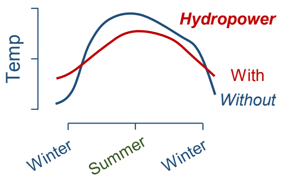
Background

Hydropower induced temperature changes

- **Reduction in summer temp.**
- **Increase in winter temp.**

The effects can differ depending on hydropower location and local channel heterogeneity



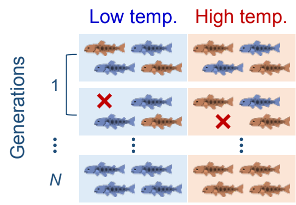
Wüest (2010) Downstream Relevance of Reservoir Management. In: Bundi (eds) Alpine water

Energy strategy 2050 of Swiss government: Increase hydropower production

Importance of temperature in evolution & ecology

Temperature can affect…

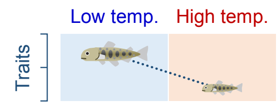
Selective pressure



Cause local adaptation

Crozier et al. (2014) Evolutionary Applications

Plasticity



Correlate with organismal functions
e.g., Diet preference, feeding rate…

Modify species interactions

Ohlberger et al. (2016) Functional Ecology

Questions

To predict hydropower effects on aquatic organisms, we will address following questions...

How are hydropower effects on temperature affected by location & local channel heterogeneity?

Hydropower and water temperature: modelling the effects of management scenario on river thermal heterogeneity
Vanzo et al., (2018)

Develop prediction model

How does temperature affect organismal traits, and consequently, modify species interactions?

Question we will address

Research plan

Study organism: Brown trout

- **Ecologically & commercially important species**

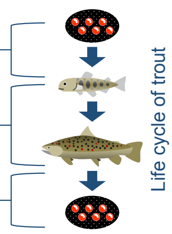
Huryn (1998) Oecologia

- **Wide altitudinal distribution range: 300 – 2000 m**

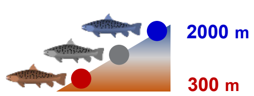
= Each local trout population may have experienced different temperature regime through many generations

What we will examine

1. **How temperature affects**
   a) **Embryonic development**
      - Laboratory common garden experiment
   b) **Larval growth & trophic interactions**
      - Field transplant experiment
   c) **Reproduction**
      - Field observation



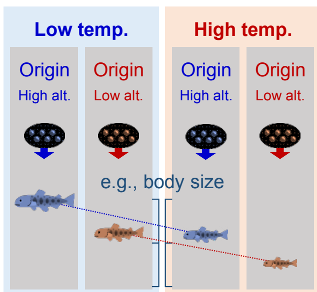
2. **How temperature effects differ among altitudinal populations**



Experiments

< 1-a & 2 >
Laboratory common garden experiment

- Temperature treatments: High & Low
- Altitudinal populations: 18 populations (300-2000 m)
- Focal traits: Size, yolk volume, timing.... at hatching & emergence

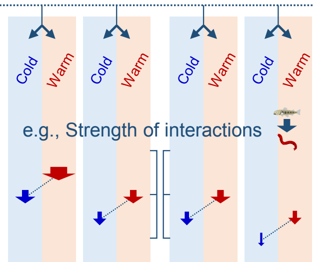


Temperature effects on body size: negative
Effects of altitudinal origin on body size: positive

By using hatchlings of common garden experiment....

< 1-b & 2 >
Field transplant experiment

- Experimental streams: Cold & warm streams
- Focal traits: Size, morphology, mortality...
- Focal interactions: Trout - their prey interactions



Temperature effects: positive
Effects of altitudinal origin: positive
Temperature during embryonic period: negative

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Künstliches Hochwasser und Geschiebeschüttungen in der Saane

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EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Hindergrund und Motivation

Im Rahmen der Energiestrategie 2050 soll die Wasserkraft in der Schweiz ausgebaut werden. Erneuerungen in Gewässerschutzgesetz und -verordnung (GSchG, GSchV) verpflichten Kraftwerksbetreiber Massnahmen gegen Probleme betreffend Schwall & Sunk, Restwasser, Fischwanderung und Geschiebedurchgängigkeit zu ergreifen. Zudem sollen verbaute Fliessgewässer so weit wie möglich revitalisiert werden.
In Zusammenarbeit mit dem Energieversorger Groupe e und des Kanton Fribourgs, wurde im September 2016 eine Reaktivierung der Auen mittels eines künstlichen Hochwassers und Geschiebeschüttungen in der Saane unterhalb der Staumauer Rossens getestet.

Übersicht

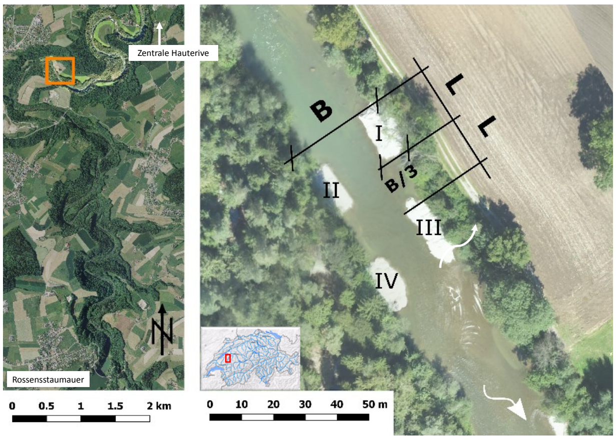

*Abb. 1: **(LINKS)** Saane zwischen der Staumauer Rossens und der Kraftwerkszentrale Hauterive. Der Projektperimeter der Schüttungen ist gelb markiert. **(RECHTS)** Die Schüttungen erfolgten in vier Depots, welche als mäandrierende Bänke angeordnet wurden. Diese Konfiguration wurde vorgängig in Laborexperimenten optimiert. Mittels gewählter Konstellation wird das Material bereits bei geringeren Abflüssen erodiert (Abflusskonzentration in der Flussmitte). Das eingebrachte Geschiebe soll zur strukturellen Habitatsvielfalt beitragen.*

Methode

- 250 m³ Geschiebe pro Depot (total 1000 m³)
- Schüttmaterial durch Aushub aus angrenzendem Auenwald (unsortiert)
- d_m = 57 mm, d_{90} = 113 mm
- 489 RFID PIT tags (passive Sensoren, gleichmässig in d_m und d_{90} verteilt)
- Tags in drei verschiedenen Schichten gleichmässig in Depots verteilt
- Nach Hochwasser, RFID PIT tags wieder finden mit Antenne
- Anschliessend: Vergleich mit Laborexperimenten
- Abflussganglinie mit Maximalem Abfluss 195 m³/s (Wiederkehrperiode: 1 Jahr)

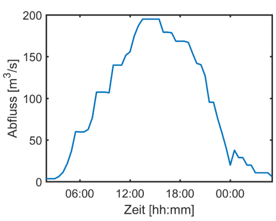

Abb. 2: Abflussganglinie des künstlichen Hochwassers. Der Spitzenabfluss von 195 m³/s entspricht einem jährlichen

Geschiebetransport & Erosion

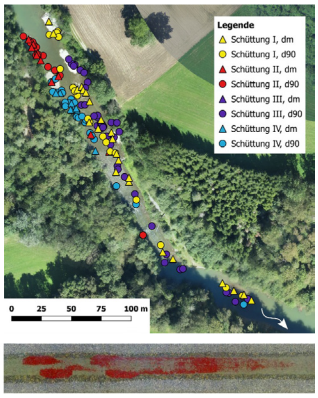

Abb. 3: Verteilung der RFID Pit tags nach dem Hochwasser.

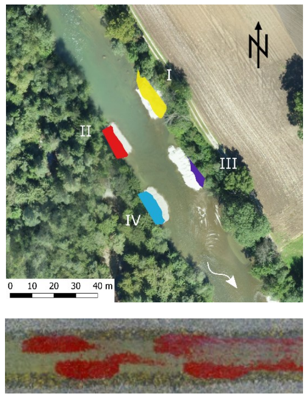

Abb. 4: Erosion der Depots nach dem Hochwasser.

Als Vergleich der Laborbersuch nach 60 min. Mehr informationen zu den Laborversuchen in der Doktorarbeit von Elena Battisacco (LCH-EPFL Communication 67)

Analysen

- 277 RFID PIT tags wiedergefunden (166 transportiert, 111 auf den Depots)
- Resultate bestätigen Laborversuche
- Kein Transport quer zur Fliessrichtung
- Depot III praktisch vollständig erodiert
- Linksufrige Depots stärker erodiert und weiter transportiert

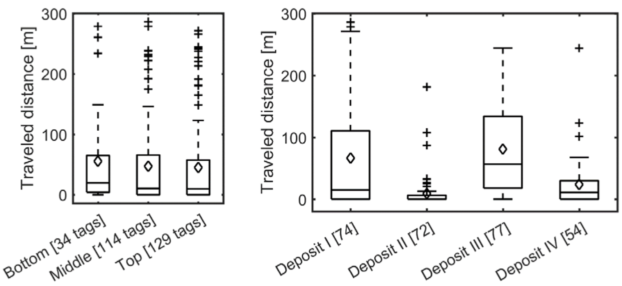

Abb. 5: Distanzen, welche die markierten Steine zurückgelegt haben nach Position in den Depots (links): unten (bottom), mitte (middle) und Oberfläche (top) und nach Herkunftsdepot (rechts).

Erkenntnisse

Trotz unterschiedlichen Randbedingungen, bestätigen die **Resultate des Feldversuches die Laboruntersuchungen**. Das Hochwasser war nicht stark genug, um alle Schüttungen zu erodieren. Die Depots am linken Ufer wurden stärker erodiert und das Material weiter transportiert, was auf die Anordnung der Depots unterhalb einer starken Rechtskurve im Fluss zurückzuführen ist.

Danksagung

Dieses Forschungsprojekt wird im Rahmen des Nationalen Forschungsprogramms „Energiewende“ (NFP 70) des Schweizerischen Nationalfonds (SNF) durchgeführt. Weitere Informationen zum Nationalen Forschungsprogramm sind auf www.nfp70.ch zu finden. Die Laborversuche wurden von Dr. Elena Battisacco durchgeführt. Dr. Diego Tonolla und Dr. Michael Döring sowie an die kantonalen Behörden Fribourg und den Kraftwerkbetreiber Groupe e wird für ihre Zusammenarbeit im Zusammenhang mit dem künstlichen Hochwasser gedankt.