Task 2.1

Title

Morpho-climatic controls

Projects (presented on the following pages)

Multiple-purpose use of reservoirs in high alpine areas under climate change: a national view
Manuela Brunner, Astrid Björnsen Gurung, Massimiliano Zappa, Manfred Stähli

High resolution climate scenarios for snowmelt modelling in small alpine catchments
Michael Schirmer, Nadav Peleg

The role of glacier retreat for Swiss hydropower production
Bettina Schaefli, Pedro Manso, Mauro Fischer, Matthias Huss, Daniel Farinotti

Ice volume and bedrock topography estimation of the Swiss glaciers
Melchior Grab, Andreas Bauder, Lino Schmid, Lasse Rabenstein, Lisbeth Langhammer, Kevin Délèze, Philipp Schaer, Patrick Lathion, Hansruedi Maurer

HEPS4Power - Extended-range Hydrometeorological Ensemble Predictions for Improved Hydropower Operations and Revenues
Samuel Monhart, Philippe Gerber, Frédéric Jordan, Christoph Spirig, Massimiliano Zappa

Sub-seasonal hydrometeorological ensemble predictions in small- and medium size mountainous catchments: Benefits of the NWP approach
Samuel Monhart, Massimiliano Zappa, Christoph Spirig, Christoph Schär, Konrad Bogne

Changes in future river sediment yield: preliminary results from the Guerbe river
Nadav Peleg, Jorge Ramirez

Simulating climate at high spatial and temporal resolutions using the new CH2018 climate scenarios
Nadav Peleg, Paolo Burlando

Online prediction tool for hydropower energy (Opt-HE)
Jordan, Guillaume Artigue, Kevin Cros, Claude-Aline Loetscher, Oriane Etter, Anton Schleiss

Helicopter-borne ground-penetrating radar surveying of temperate Alpine glaciers
Lisbeth Langhammer, Lasse Rabenstein, Lino Schmid, Melchior Grab, Andreas Bauder & Hansruedi Maurer

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Multiple-purpose use of reservoirs in high alpine areas under climate change: a national view

Manuela Brunner, Astrid Björnsen Gurung, Massimiliano Zappa, Manfred Stähli
(Swiss Federal Research Institute WSL)

Background

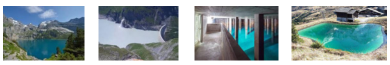
The drought of the past months (summer 2018) rise our awareness for the anticipated impacts of climate change on Alpine water resources associated with an increased probability of local water shortages towards the end of this century. The negative effects of runoff regime shifts triggered by rising temperature, reduced snow pack and glacier cover might be alleviated by the multiple-purpose use of reservoirs for electricity production, irrigation, snow-making, drinking water supply, ecological needs, or flood control. We investigate the potential role of such multiple-purpose reservoirs for alleviating water shortages.

The present study – issued by the Federal Office of the Environment FOEN – aims at providing a country-wide assessment of this potential by comparing the seasonal availability of water in reservoirs to the total demand of water by different users in the adjacent area.

Data and Methods

Water availability A
- calculated on a monthly and yearly time resolution, for current and future climate conditions (new scenarios CH2018), using the numerical model PREVAH (Viviroli, D., Zappa, M., et al. 2009)

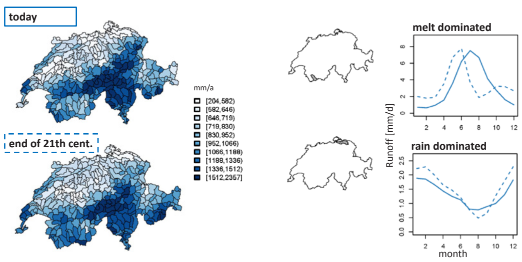
Reservoirs B
- calculated based on available inventories and statistics by the FSO (2017)



Water demand C
- calculated based on methods and data from the NRP 61 and FSO (2017)

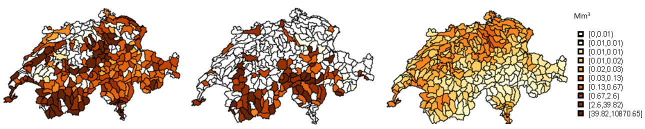
Results

A **Water availability in Switzerland**:

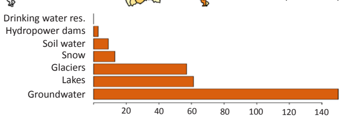


B **Existing water reservoirs:**

Natural lakes: Hydropower reservoirs: Drinking-water reservoirs:

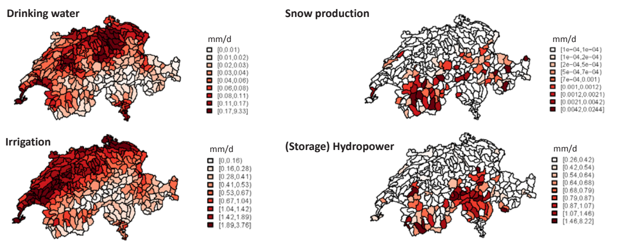


Total storage volume (Gm^3):

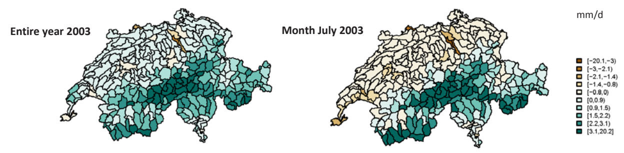


Data on natural storage volumes from Björnsen & Stähli (2014)

C **Water demand**

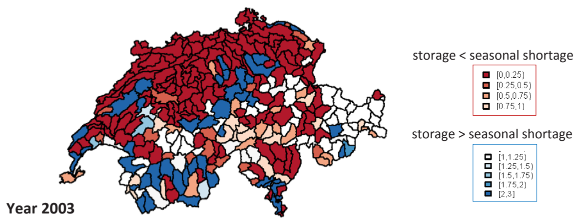


D = A Water availability - C Water demand



Water scarcity: water demand > water availability only consumptive use and ecological flow

D B **Potential of reservoirs for alleviating water shortages**



Red sub-areas don't have enough reservoir storage capacities to alleviate water shortages, such as in 2003.

Blue sub-areas have considerable storage compared to estimated seasonal shortage. Here, there is potential to alleviate water shortage in adjacent regions (downstream).

Discussion

A regional comparison of water availability, water reservoirs and water demand – on a monthly time scale – reveals areas with seasonal water shortage and can indicate where (available or future) reservoirs can alleviate seasonal water shortage.

The present results do not consider water transfers between sub-areas.

More specific calculations (including water transfer within and between sub-areas) will be made for Val de Bagnes (VS), Surses (GR) and a region in the Swiss plateau.

Acknowledgement

- Funding from Federal Office of the Environment (FOEN), (Focus area NCCS – CH2018 Hydro)
- Meteorological Data from MeteoSwiss
- Innosuisse (CTI) through SCCER Supply of Electricity (Task 2.1)
- This project is elaborated in close collaboration with HSR Rapperswil

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High resolution climate scenarios for snowmelt modelling in small alpine catchments

Michael Schirmer, Nadav Peleg

Motivation

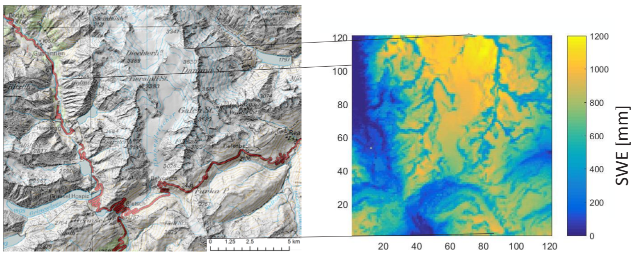
The aim of this project is to support economic risk assessments of long-term investments by small hydropower plant (SHP) operations due to a changing climate. We estimate the impact of climate change on snow water equivalent (SWE) and snowmelt using an innovative combination of novel components: a stochastic 2-dimensional weather generator, and a high-resolution energy balance snow cover model. This allows to include relevant uncertainty sources at a local scale (e.g. natural climate variability).

Methods

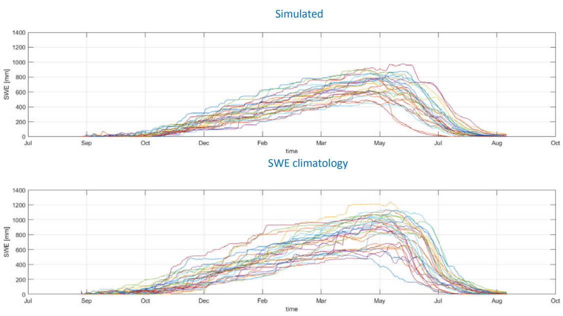
Future climate scenarios are generated based on newest global and regional climate models for the extreme RCP8.5 scenario for the mid and the end of this century. Multiple realisations of future climate periods (30 years) are considered to assess the irreducible impact of natural climate variability. The likelihood of a single winter in a future climate (or of a climate period of 30 years) to be significantly different to our current climate can be assessed.

The model chain in high resolution (100 m x100 m) ensures that relevant processes are considered as for example terrain shading of shortwave radiation, realistic space-time structure of precipitation fields influenced by orographic enhancement, as well as redistribution of snow by wind based on terrain roughness.

Location and spatial model output example

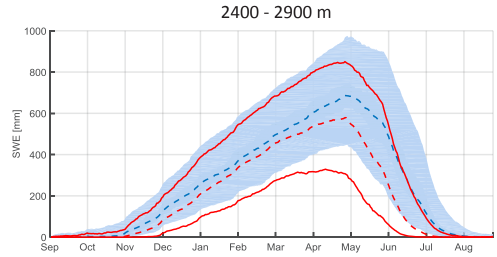


Model results against 'observations'



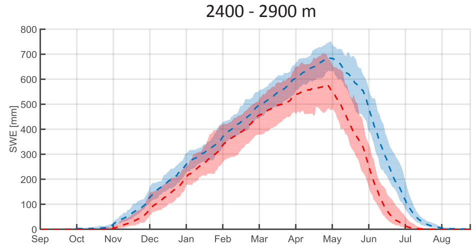
- SWE of 30 years in an elevation band of 2900 to 3400 m
- Dynamics well preserved
- Conservative spread between the years
- Approx. 10% less precipitation (under further investigation)

Natural variability of single years – mid of century



- Simulated SWE (5, 50,95 percentiles)
- Current climate (blue), 900 years
- Future climate (red), 5 climate models (RCP8.5) x 300 years
- The spread between dry and wet years is substantially larger than the effect of climate change.
- This spread evolves mainly from natural variability.
- A relevant change between current and future climate can be observed during melt season, while the amount of SWE is not changing relevantly.
- Changes are more evident in lower elevation bands, however, in the shown band most of SWE is stored.

Variability/Uncertainty of climate period predictions



- Same as above, however, the spread of median values of 30-year blocks are analyzed (5 and 95 percentiles) , i.e.:
- "How uncertain are our predictions of a future climate including natural variability and climate model uncertainty?"
- Overlapping areas can be interpreted as a likelihood of no change in SWE between the current und future climate period.
- Mid of this century there is a substantial likelihood of having as much snow as today during peak winter, although considering the extreme climate scenario RCP8.5. However, a substantial change in average melt out is very likely.
- Both natural climate variability and climate model uncertainty contribute to this range.

Conclusion and Outlook

- Natural climate variability is responsible for single years to be different from another. Also whole climate periods of 30 years may be dryer or wetter.
- We quantified the effect of natural variability and climate model uncertainty. We can conclude that it is quite uncertain that there will be less SWE in a substantially warmer climate (RCP8.5, mid if this century) in the presented elevation range (2400 - 2900 m).
- **For the end of this century RCP8.5 scenarios show a significant change in the amount of SWE for all elevation bands.**
- We want to answer, for which climate scenario and for which elevation ranges the impact of climate change is clearly visible, and how this uncertainty in SWE can be translated to runoff.

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The role of glacier retreat for Swiss hydropower production

Bettina Schaefli[1], Pedro Manso[2], Mauro Fischer[3,4], Matthias Huss [3,5] Daniel Farinotti [5,6]
1: University of Lausanne, 2: EPFL, 3: University of Fribourg, 4: University of Zurich, 5: ETHZ, 6: WSL

Motivation

- High elevation hydropower production (HP) strongly relies on water resources that are influenced by glacier melt
  ⇨ High sensitivity to climate warming
- First Swiss-wide quantification for the share of Alpine hydropower production that directly relies on the waters released by glacier mass loss
  ⇨ HP from depletion of long-term ice storage that cannot be replenished by precipitation in the coming decades

Data sets

- HYDROGIS database of the Swiss HP infrastructure (Balmer, 2012)
  ⇨ 401 powerhouses grouped into 284 HP schemes, total installed power of 14.5 GW (Fig. 1)
- Swiss hydropower production statistics (Swiss Fed. Office for Energy, 2016),
  ⇨ Aggregated to 6 regions: Ticino, Grisons, Valais, Northern Alps, Jura, Plateau
- Swiss-wide raster data set (500 m x 500 m) of monthly natural streamflows for the period 1981-2000 (Zappa et al., 2012)
- Geodetic glacier mass changes of all glaciers between 1980 & 2010 (Fischer et al., 2015); Swiss Glacier Inventory SGI 2010 (Fischer et al., 2014)
- Simulated past & future glacier runoff (GloGEM, Huss & Hock, 2015)
  ⇨ Model forced with ERA-interim climate re-analysis data for past
  ⇨ Future simulations (2040 – 2060, 2070 – 2090) with 14 Global Circulation Models and three different CO2-emission pathways

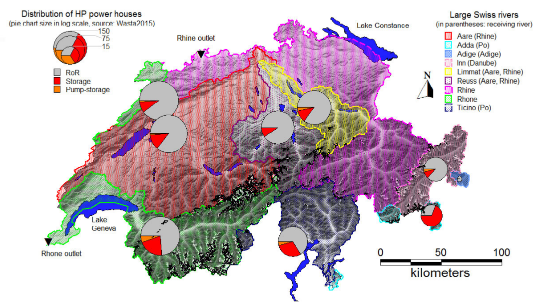

Fig. 1: Swiss HP infrastructure according to main catchments and HP type

Methods

- Hydropower production $E(t)$ from a given runoff $Q(t)$ estimated via *electricity coefficient,* γ [kWh m^{-3}] (energy conversion factor):

(1) $$E(t) = \gamma Q(t)$$

- Glacier melt HP share estimated as: (2)

$$\rho = \frac{E_m}{E_q} = \frac{V_m}{V_q}$$

m: glacier melt (index)
q: total runoff (index)
V: runoff volume, m^3 yr^{-1}

(second equality holds from linearity assumption, eq. 1)

- Estimation of γ_h [kWh m^{-3}] at powerhouse scale * indicates design variables

(3) $$\gamma_h^* = \frac{E_h^*}{Q_h^* \tau_h^* 3600 \cdot 10^3} = \frac{P_h^*}{Q_h^* 3600 \cdot 10^3}$$

E_h^*[Wh yr^{-1}]: expected annual electricity production
P_h^* [W]: total available power
Q_h^* [m^3 s^{-1}]: total design discharge through turbines
τ_h^* [h yr^{-1}]: powerhouse operating hours (estimated)

- Estimation of scheme-scale γ_j & *regional* γ_r :

(4) $$\widehat{\gamma}_j = \frac{\sum_{\forall h \in j} E_h^*}{3600 \sum_{\forall h \in j} Q_h^* \tau_h^*} = \frac{\sum_{\forall h \in j} \gamma_h^* Q_h^* \tau_h^*}{\sum_{\forall h \in j} Q_h^* \tau_h^*}$$

(5) $$\widehat{\gamma}_r = \frac{\sum_{\forall j \in r} \widehat{\gamma}_j E_j^*}{\sum_{\forall j \in r} E_j^*}$$

Results

- Very high electricity coefficients for glacier catchments (Fig. 2a), regional relationship of electricity coefficients vs catchment elevation (Fig. 2b)

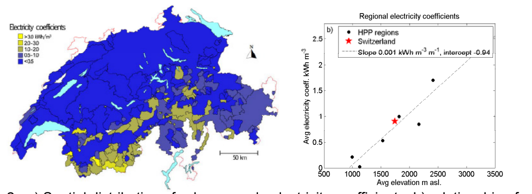

Fig. 2: a) Spatial distribution of scheme-scale electricity coefficients, b) relationship of regional electricity coefficient swith average elevation

- **Regional estimate of HP from glacier mass loss**
  ⇨ Avg glacier mass loss 1980-2010 (CH): 0.62 m yr^{-1} (water equivalent)
  ⇨ Avg glacier elevation 2010: 3042 m asl ⇨ average electricity coefficient (trend fig. 2b): 2.11 kWh m^{-3}
  ⇨ Avg glacier extent 1980-2010: 1072 km^2
  ⇨ Glacier loss HP: 2.11 kWh m^{-3} x1072 km^2 x0.620 m yr^{-1} = 1.4 TWh yr^{-1}
- **Catchment-scale estimate of HP from glacier mass loss** (Fig. 3)
  ⇨ CH average 1980-2010: 1.3 TWh yr^{-1} or 3.8 % of annual HP, reduction to 0.4 TWh yr^{-1} by 2070 – 2090 (Fig. 4)

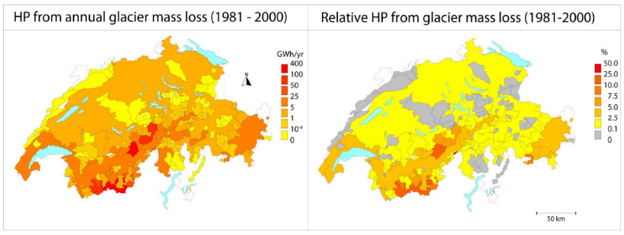

Fig. 3: Left: HP from glacier mass loss in GWh yr^{-1} for the period 1981-2000, right: HP production ratios ρ_{ij} from glacier mass loss for the same period.

- Regional differences in shares and timing of decline (Fig. 4)

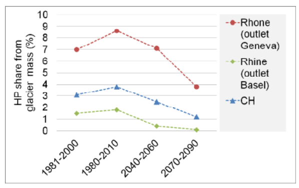

Fig. 4: HP share from glacier mass loss for different periods, for selected large catchments (*attention: time scale not linear*)

Conclusion

Swiss-wide HP from glacier mass loss since 1980 around 1.4 TWh yr^{-1}
⇨ Reduction to 0.4 TWh yr^{-1} by 2070 – 2090
Future reduction of HP from glacier mass loss
⇨ Same order of magnitude as reduction expected from application of water protection act

Reference: Schaefli, B., Manso, P., Fischer, M., Huss, M., and Farinotti, D.: **The role of glacier retreat for Swiss hydropower production**, Renewable Energy, 132, 615-627, 2019

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Ice volume and bedrock topography estimation of the Swiss glaciers

M. Grab[1,2], A. Bauder[2], L. Schmid[1,2], L. Rabenstein[3], L. Langhammer[1], K. Délèze[4], P. Schaer[4], P. Lathion[4], H.R. Maurer[1]

[1]Institute for Geophysics, ETH Zurich [2]Laboratory of Hydraulics, Hydrology and Glaciology, ETH Zurich [3]Drift & Noise Polar Services GmbH, Bremen [4]Geosat SA, Sion

1. Overview

For overcoming future challenges arising from the ongoing melting of glaciers, an accurate prediction of the future river discharge and the topography of deglaciating regions is needed. A good knowledge of the current ice thickness distribution builds the basis for such predictions.

We developed a helicopter-borne ground penetrating radar (GPR) device and implemented the software for data processing and glaciological modeling. The ice thickness of glaciers is measured with the GPR on a sparse grid. The data is then used as input for glaciological modeling, to calculate continuous ice thickness maps. The goal of the project is to estimate the total ice volume in the Swiss Alps and to deliver information about the glacier bed topography.

2. Current status of the project

Fig. 1 schematically shows the components of the project. The following capabilities build the "pillars" of the project:

- Instrumentation for GPR-surveying (e.g. Langhammer et al., 2017)
- Data processing software (e.g. Grab et al. 2018):
- GIS-based database.

They have been completed in 2017. For more detailed information, we refer to the SCCER-SoE conference contributions from previous years. Based on these "pillars", we have worked on the "roof" during 2017 and 2018. The main focus was on:

- GPR data acquisition and processing
- Implementation of the GlaTE algorithm

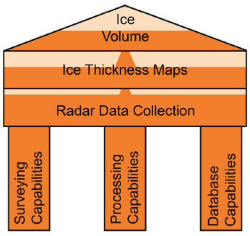

Figure 1: Left: Project *sketch. Acquiring of ice thickness data (roof), based on surveying, processing and database capabilities (pillars). Completed sections shaded in dark. Right: The GPR-instrument during a mission in spring 2018.*

3. Data acquisition and processing

To date, a total of around 1'000 km of GPR profiles has been recorded on glaciers all over the Swiss Alps. A data example is shown in Fig. 2. It was recorded in Spring 2017 in the tongue area of the Morteratsch glacier. GPR-reflections from the bedrock are marked with arrows. Together with data recorded in earlier years (1999-2015, around 1'400 km), the database now comprises data for most glaciated regions in Switzerland (see Fig. 3):

- 2016-2018: +/- complete data coverage of the corresponding glaciers
- 1999-2016: +/- complete data coverage (blue in Fig. 3) or partial data coverage due only partial surveying or limited data quality (light blue).

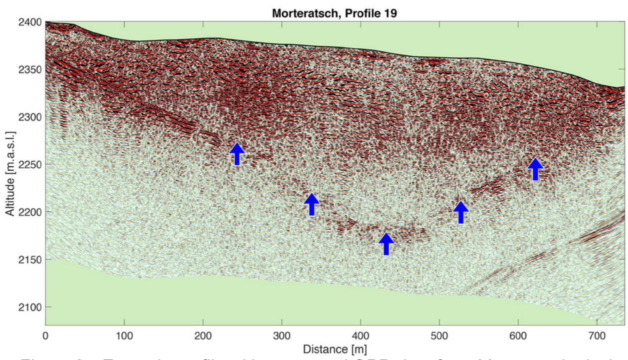

Figure 2: Example profile with processed GPR-data from Morteratsch glacier. Bedrock interpretation indicated by blue arrows.

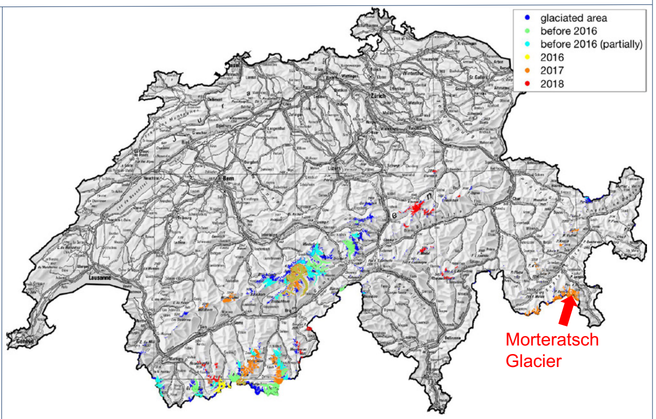

Figure 3: Current (September 2018) status of the data acquisition. Colors indicate the year of the most recent GPR-recording for a specific glacier.

4. Continuous ice thickness maps – the GlaTE algorithm

The GPR data are recorded on a sparse grid across the glaciers. For estimating the ice thickness h_{est} on continuous maps, an interpolation between the GPR profiles is needed. The interpolation procedure should take into account the dynamics of the ice flow and the conservation of mass, given by the ice thickness h_{mod} from glaciological modeling. Simultaneously, it should also adequately account for the ice thickness measured with GPR, h_{GPR}. Therefore, an inversion problem has been formulated for estimating the ice thickness h_{est} while considering a unlimited number of constrains, using the relationship

$$\begin{bmatrix} \lambda_1 \boldsymbol{G} \\ \lambda_2 \boldsymbol{L} \\ \lambda_3 \boldsymbol{B} \\ \lambda_4 \boldsymbol{S} \end{bmatrix} h_{est} = \begin{bmatrix} \lambda_1 h_{GPR} \\ \lambda_2 \nabla h_{mod} \\ 0 \\ 0 \end{bmatrix}$$

In our case, we implemented four different constrains, each weighted by λ_i in order to account for its specific confidence. The constrains are:

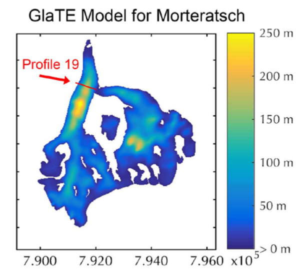

Figure 4: Ice thickness for Morteratsch glacier resulting from GlaTE modeling

1. ice thickness from GPR measurements, h_{GPR}, obtained at the locations $\boldsymbol{G}$
2. gradient of the modelled ice thickness, ∇h_{mod}, at locations $\boldsymbol{L}$
3. glacier boundary $\boldsymbol{B}$ where the ice thickness is zero,
4. smoothness constrain using the smoothness matrix $\boldsymbol{S}$

This inversion procedure builds the core of the GlaTE (Glacier Thickness Estimation) algorithm, which we implemented into our data processing software suite.

A more detailed description is given by L. Langhammer (2018), together with several application examples (e.g. Morteratsch glacier, Fig. 4).

5. Outlook

The data processing of all the recorded GPR-data is accomplished and we are currently completing the interpretation. The resulting bedrock information is used for GlaTE modeling to obtain the ice volume of each glacier and finally to provide the total ice volume in the Swiss Alps. For the near future, some more campaigns are planned to fill the major gabs in the database (blue and light blue parts in Fig. 3).

Acknowledgments: The authors thank BRTECHNIK and C. Bärlocher for constructing the GPR-platform. Financial support was provided by ETH Zurich, the Swiss Geophysical Commission, and SCCER-SoE/Innosuisse.

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HEPS4Power Extended-range Hydrometeorological Ensemble Predictions for Improved Hydropower Operations and Revenues

Samuel Monhart[1,2,3], Philippe Gerber[4], Frédéric Jordan[4], Christoph Spirig[2], and Massimiliano Zappa[1]

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What is the value of sub-seasonal streamflow forecasts?

In the framework of the NRP70 project HEPS4power, hydrometeorological ensemble predictions for up to one month in advanced are used for the optimization of hydropower system.

In this poster the added value of using sub-seasonal hydrometeorological streamflow predictions is presented.

Problem: Combine the sub-seasonal streamflow prediction with hydropower optimization procedures and assessement their economic value.
Method: Compare the revenues resulting from the optimization with different streamflow forecasts (Climatology, NWP-hydro-chain, Reference)
Goal: Determine the added value of sub-seasonal streamflow predictions for hydropower operations in term of its revenues.

Methods

Meteorological predictions:
- Sub-seasonal ECMWF IFS Cy40r1 predictions (up to 32 days, 50km spatial resolution)
- Operational predictions from April 2014 – March 2015 (51 members)
- Corresponding 5-member reforecasts (1994-2014)

Pre-processing: (See Poster by Monhart et al. for details)
- Leave one year out crosscalibration of the reforecasts using QM
- Gridded observations for precipitation and temperature (2km spatial resolution → downscaling)

Hydrological modelling:
- 2 Hydrological models: Routing System and PREVAH

Optimization Scenarios:
- *Climatological scenario:*
  Optimization with climatological streamflow data
  → lower benchmark scenario
- *Reference Simulation:*
  Optimization with streamflow from hydrological model runs with observed meteorological inputs
  → upper hydrological benchmark
  (best possible scenario given the hydrological model)
- *Perfect scenario:*
  Optimization with observed streamflow
  →upper optimization benchmark
  (best possible scenario given the optimization scheme)

Optimization

Release schedule based on two key factors at each time step
- **Lake level** difference to predefined target level (multiannual optimum)
- **Price** difference to optimum fixed cost (p)

Algorithm steps:

1. *Compute the maximal theoretical release time over the optimization lead time*
2. *Identify the period with highest prices*
3. *Adapt the prices identified in point 2 using a correction factor ($c(t)$) depending on the current lake level ($h(t)$), the target level (h_{target}) and the level elasticity factor (c_l):*
$$c(t) = 1 - c_l \frac{h(t) - h_{target}}{h_{target}}$$
4. *Release decision if $p_t \geq p * c(t)$*

If the lake level is above close to or above spill level a release is always scheduled.

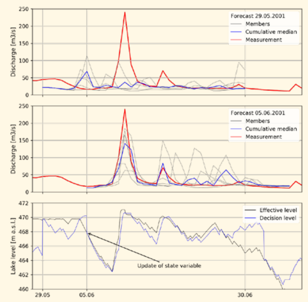
Tor run this deterministic optimization scheme, the ensemble members of the prediction is not individually used. Therefore, the cumulative median of the members is determined and used for the optimization scheme. In the cumulative median, the flow peaks are not smoothed out.

Hydrological model performance for the period 1994-2014

	NSE	NSElog	MAE [m³/s]	Bias [m³/s]
Routing System	0.78	0.81	4.37	-0.25
PREVAH	0.81	0.88	3.58	0.55

Different scores to characterizing the performance of the hydrological reference simulations
(Nash-Sutcliffe Efficiency (NSE) range from -∞ to 1 with best score NSE = 1 and forecast not better than climatology NSE = 0 ; NSElog = logarithmic NSE; MAE = Mean Absolute Error, Bias = Mean Error)

Example optimization:



Optimization for two selected forecast dates. The lake level evolution is shown at the bottom.
"Effective level" = lake level using the real inflows with the optimized release schedule.
"Decision level" = forecasted lake level using the forecasted inflows

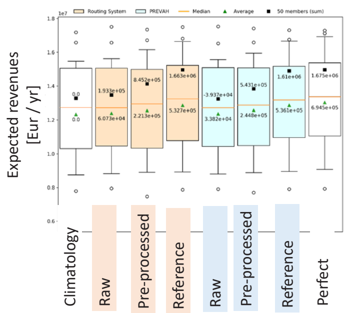
Result

Added value of forecasts up to 4% gain in annual revenues

Importance of pre-processing temperature and precipitation

Gain related to reduction in spill

Optimization using the individual (single) members and considering the median optimized release yields similar results



Reforecasts (1994-2014) | Forecasts (2014-2015)

Annual revenue [€]

Scenario	Average	%	Maximum	Minimum	50 - members	%
Perfect	13 021 640	5.63	17 281 660	6 202 512	14 962 930	12.61
RS-raw	12 387 832	0.49	17 505 610	6 087 720	13 480 970	1.45
RS-pre.pro.	12 548 403	1.80	17 335 520	5 961 600	14 132 910	6.36
RS-Reference	12 859 760	4.32	17 491 140	6 135 936	14 950 280	12.51
PREVAH-raw	12 360 925	0.27	17 523 510	6 101 584	13 248 330	-0.30
PREVAH-pre.pro	12 571 910	1.99	17 409 160	6 078 352	13 830 790	4.09
PREVAH-Reference	12 863 205	4.35	17 301 080	6 153 392	14 897 960	12.12
Climatology	12 327 106	-	17 172 260	6 076 344	13 287 700	-

Revenues of the different scenarios

Annual spillings [m³]

Scenario	Average	%	Maximum	Minimum	50 - members	
Perfect	5 405 893	-79.8	21 265 600	-	22 972 530	-75.01
RS-raw	25 478 477	-4.6	76 758 910	-	81 201 090	-11.67
RS-pre.pro.	14 951 113	-44.0	48 374 460	-	59 680 630	-35.08
RS-Reference	11 860 118	-55.6	39 943 700	-	17 342 580	-81.14
PREVAH-raw	27 179 920	1.8	77 175 540	-	91 145 620	-0.85
PREVAH-pre.pro.	17 701 706	-33.7	57 759 500	-	70 060 040	-23.79
PREVAH-Reference	8 934 071	-66.5	31 110 160	-	23 202 080	-74.76
Climatology	26 700 997	-	73 906 930	-	91 930 850	-

Spill in the different scenarios

Conclusion, Discussion and Outlook

- Sub-seasonal ensemble predictions can provide an added value for hydropower operations.
- Positive effects of pre-processing (Bias correction and downscaling)
- Limiting factor: the prices used in this study are observed historical prices. Thus, this added value can be expected if the future price is known. The impact of a price forecast should be considered in further studies.

Outlook:
- Probabilistic optimization instead of deterministic
- Additional post-processing (statistical correction of the hydrological output) could further enhance the performance of the streamflow forecasts and thus increase the value of the forecast.

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Sub-seasonal hydrometeorological ensemble predictions in small- and medium size mountainous catchments: Benefits of the NWP approach

Samuel Monhart[1,2,3], Massimiliano Zappa[1], Christoph Spirig[2], Christoph Schär[3] and Konrad Bogner[1]

Swiss Federal Research Institue, WSL, Federal Office of Meteorology and Clinmatology, MeteoSwiss, ETH Zurich, Institute for Atmospheric and Climate Science

How well can we forecast streamflows 1 month in advance?

In the framework of the NRP70 project *HEPS4Power* hydrometeorological ensemble predictions for up to one month in advanced are used for the optimization of hydropower system (see separate Poster).

In this poster, the streamflow predictions used to run the optimization scheme are analysed in terms of their performance:

- **Problem:** optimal combination of meteorological and hydrological models
- **Method:** Bias correction and Downscaling of meteorological forecast using Quantile Mapping (QM)
- **Goal:** Characterization of the skill / performance of the resulting streamflow predictions and comparison with a traditional Ensemble Streamflow Prediction (ESP) system

Methods

Meteorological predictions:

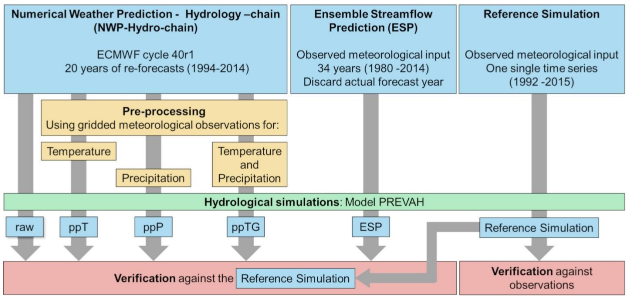
- Sub-seasonal ECMWF IFS Cy40r1 predictions (up to 32 days)
- Operational predictions from April 2014 – March 2015 (51 members)
- Corresponding 5 member reforecasts (1994-2014)

Pre-processing:

- Leave one year out crosscalibration of the reforecasts using QM
- Gridded observations for precipitation and temperature

Hydrological modelling:

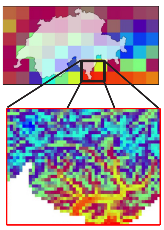
- Hydrological model PREVAH
- Traditional Ensemble Streamflow Prediction System (ESP)
- Reference Simulation for verification



Downscaling

Quantile Mapping (QM)

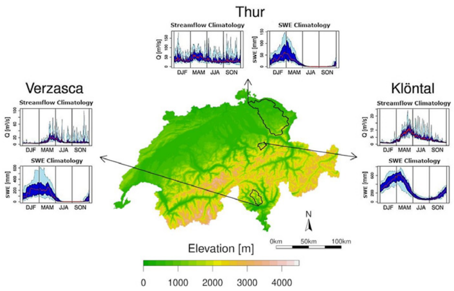
Raw
(20 km spatial resolution)



Downscaled
(2km spatial resolution)

Catchment characteristics

System analysed for 3 catchments with different hydroclimatic conditions



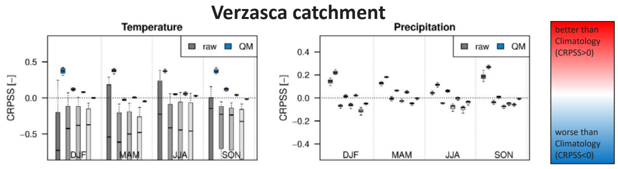
		Verzasca	Klöntal	Thur
Catchment area [km2]		185	83	1696
altitude range [m]	Maximum elevation	2864	2883	2505
	average elevation	1651	*NA*	770
	minimum elevation	490	847	356
dominant hydroclimatic regime		snow	snow and glacial	precipitation

Results

Meteorological forecast performance

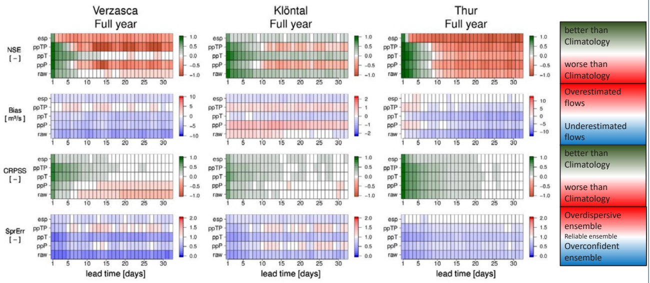
- Importance of statistical correction (meteorological post-processing)
- Positive skill in terms of CRPSS up to 3 weeks for weekly mean temperature and 1 week for precipitation

Verzasca catchment



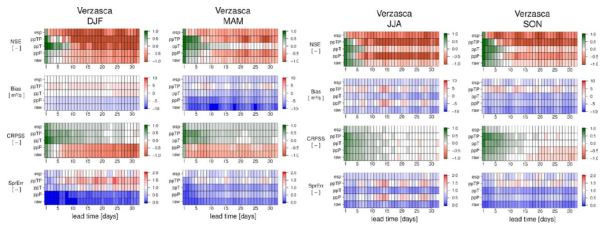
Hydrological forecast performance

- Importance of statistical corrections (hydrological pre-processing)
- NWP-hydro approach outperforms traditional ESP
- Importance of correcting both temperature and precipitation
  →precipitation important to correct ensemble spread
- Pre-processing effect on performance is more pronounced in snow-dominated catchments
- Different verification Scores need to be taken into account



Seasonal differences in performance:

- Best performance in MAM and DJF → pronounced effect of pre-processing
- Importance of snow-related processes



Conclusion

- Meteorological forecast performance is limited to 3 weeks for temperature and 1 week for precipitation.
- NWP-hydro chain can provide skilful predictions up to 30 days, depending on catchment characteristics and season.
  →non-linear propagation of the meteorological forecast skill to streamflow forecast skill
- Best performance and largest effect of the pre-processing are found in winter (DJF) and spring (MAM)

→Such prediction system have a great potential for different applications where the forecast performance can further translate into forecast value. Such an example is presented in the poster describing the project HEPS4power for hydropower optimization (Monhart et al.). Furthermore, forecast of droughts could benefit from such a pre-processing as well (see poster by Zappa et al.).

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Changes in future river sediment yield: preliminary results from the Guerbe river

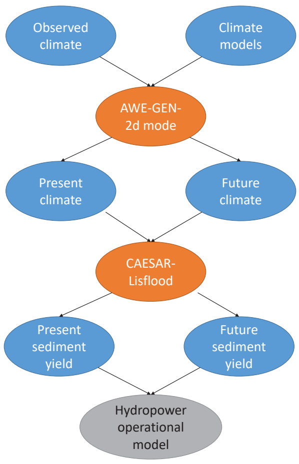
Nadav Peleg, Jorge Ramirez

Motivation

Fine sediments affect the operation of small river hydropower turbine. Climate change may impact the sediment yield along rivers, as changes in rainfall intensity and occurrence are expected. Here, a modeling framework is suggested in order to explore the effect of climate change on the sediment production in rivers. The framework is tested for the Guerbe river as a feasibility study.

Modeling approach

- AWE-GEN-2d model is used to generate multiple gridded rainfall realizations for present and future climates using observed data and data from climate models.
- Climate variables generated by AWE-GEN-2d are used as input into CAESAR-Lisflood model to generate the sediment yield for present and future climates.
- Sediment yield and discharge outputs from CAESAR-Lisflood will be used as inputs into an hydropower operational model (yet to be developed).



AWE-GEN-2d model

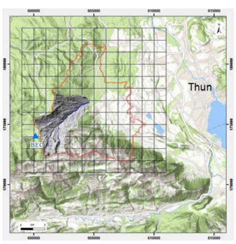
AWE-GEN-2d (**A**dvanced **WE**ather **GEN**erator for **2**-**D**imensional grid) model is a stochastic weather generator used to downscale climate variables for present and future periods using information from climate models. Further details on the model are given in the poster entitled "Simulating climate at high spatial and temporal resolutions using the new CH2018 climate scenarios" by Peleg and Burlando.

CAESAR-Lisflood model

Caesar-Lisflood is a geomorphological/Landscape Evolution Model that combines the Lisflood-FP 2d-hydrodynamic flow model that conserves mass and partial momentum with the CAESAR geomorphic model to simulate erosion and deposition in river catchments and reaches. The model operates over a wide range in space and time ($1 km^2$ to $1000 km^2$, hours to 1000 years).

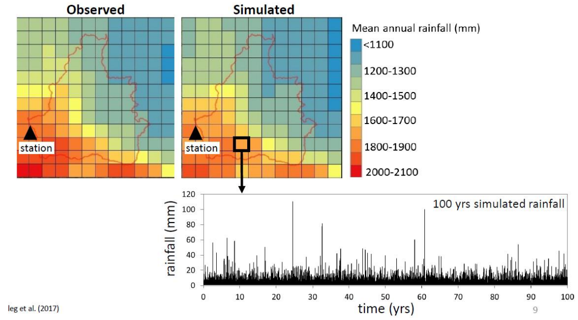
Study site: Guerbe river

Guerbe river is located in the Swiss pre-Alps, with a catchment area of $12 km^2$. Rainfall is simulated over a 12 x 12 grid cell domain (cells of $2 \times 2 km^2$) overlapping the MeteoSwiss (present climate) and CH2018 (future climate) gridded products. The hydrological model is calibrated using observed discharge and simulated rainfall. Sediment yield is estimated at the river's outlet.

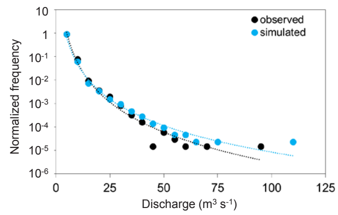


Preliminary results

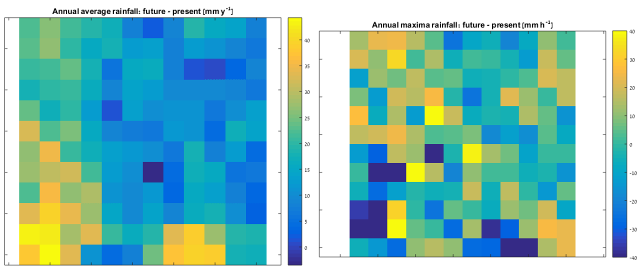
- AWE-GEN-2d model is calibrated for present climate conditions



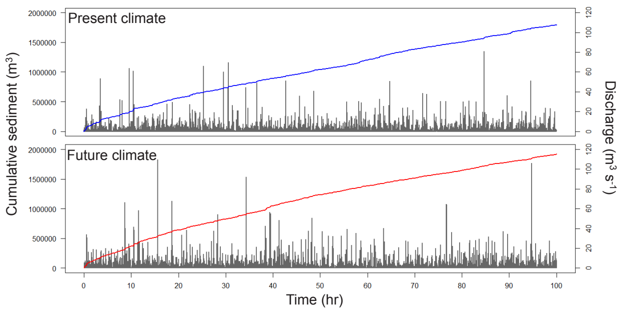
- CAESAR-Lisflood model is calibrated for present climate conditions



- AWE-GEN-2d is re-parameterize to simulate rainfall for future climate conditions (2030-2059, RCP85, multi-model mean)



- Sediment yields are computed using CAESAR-Lisflood



Final remarks

We use the Guerbe river site as a proof of concept, proving that the suggested modeling approach to simulate future sediment yield using both AWE-GEN-2d and CAESAR-Lisflood models work.

Next, a case study with a small hydropower turbine will be chosen, for which an hydropower operational model will be developed.

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Simulating climate at high spatial and temporal resolutions using the new CH2018 climate scenarios

Nadav Peleg, Paolo Burlando

Motivation

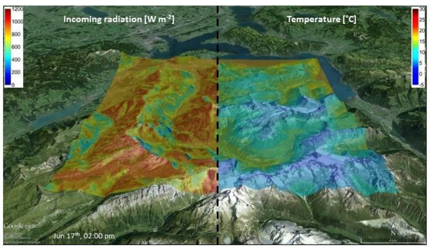
The new CH2018 official future climate scenarios for Switzerland are soon to be release (November 2018). The climate scenarios are based on analysis from Regional Climate Models (RCM) and are given at a daily and 11-km resolutions at best, with a single climate realization for each climate trajectory.

Using the new AWE-GEN-2d model, multiple stochastic realizations representing the future climate at hourly and sub-kilometre scales can be generated. By doing so we: (1) are able to simulate the climate variables needed as input for hydrological/geomorphological models at the local (catchment) scale; and (2) are able to address the uncertainty in climate emerging from the natural (stochastic) variability, which is needed to better constrain the climate impact.

AWE-GEN-2d in a nutshell

AWE-GEN-2d (**A**dvanced **WE**ather **GEN**erator for **2**-**D**imensional grid) model (Peleg et al., 2017) follows the philosophy of combining physical and stochastic approaches to generate gridded climate variables in a high spatial and temporal resolution. It is relatively fast and parsimonious in terms of computational demand.

An example of the model output (100-m and hourly) is given to the right.



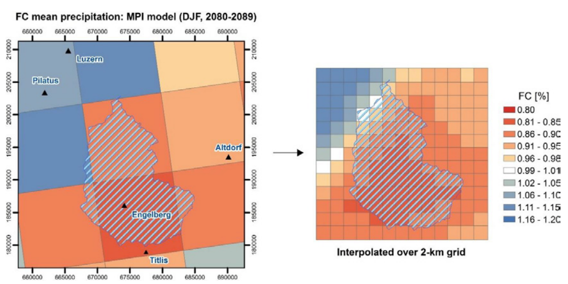
Method to re-parameterize AWE-GEN-2d

The Factors of Change (FC) approach is used for the re-parameterization of AWE-GEN-2d. It was chosen as it allows considering changes in the long-term mean and is accounting for seasonality:

$$S(h)_v^{FUT} = \frac{S(h)_v^{CLM,FUT}}{S(h)_v^{CLM,CON}} S(h)_v^{OBS} \qquad (1)$$

$$S(h)_v^{FUT} = S(h)_v^{OBS} + \left(S(h)_v^{CLM,FUT} - S(h)_v^{CLM,CON}\right) \qquad (2)$$

where S is a statistical property (e.g. mean), h is the time aggregation (daily), the subscript v is the climate variable (precipitation), the superscript FUT and CON denote future and control realization, CLM denotes the climate model, and OBS denotes the observed data. The control realization is the period for which both observed data and climate model simulations are available.

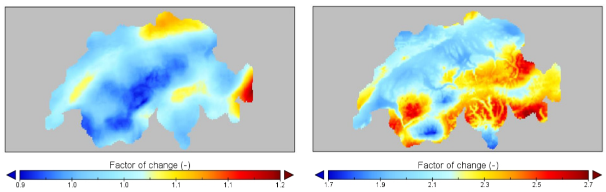


An example of the spatial interpolation of FC from an RCM grid to the AWE-GEN-2d grid is given in the figure above for the Engelberg area.

Calculating FC from the CH2018 database

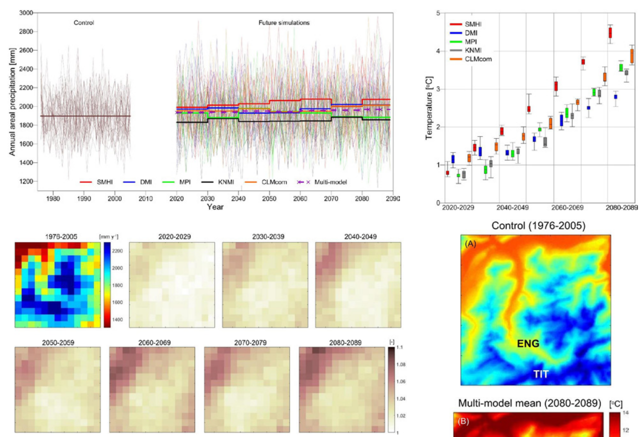
FC were computed for all RCMs in the CH2018 repository (RCP2.6, 4.5 and 8.5) on decadal (for the period of 2020-2099) and seasonal basis for the entire area of Switzerland. The FC are computed for the statistics of mean, standard deviation and occurrence of precipitation, and for mean and standard deviation of near-surface air temperature on a 2-km and daily resolution. Data is available upon request for the SCCER-SoE partners.

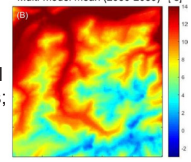
Examples for the FC of mean precipitation (left) and temperature (right) obtained from a single RCM (SMHI-RCA-ECEARTH-EUR11) for RCP8.5 and for the decade 2040-2049 are given below.



Case study

The Engelberg region was chosen as a case study to demonstrate AWE-GEN-2d abilities to simulate an ensemble of climate variables (precipitation, cloud cover, temperature, solar radiation, vapor pressure and relative humidity) for the period 2020-2089. Results for precipitation and temperature are presented below.





Clockwise order – multiple realizations of annual rainfall; temperature increase for different RCMs; decadal differences in annual rainfall at 2-km; and differences in annual temperature.

Final remarks

AWE-GEN-2d is already set for the following regions in Switzerland: Engelberg, Maggia, Thur, Kleine Emme, Gletsch, Gurbe and Oberhasli. Calibrating the model for Valais area is next in line.

High-resolution climate data will be available for the partners of SCCER-SoE upon request.

Peleg, N., Molnar, P., Burlando, P., and Fatichi, S. Exploring stochastic climate uncertainty using a gridded hourly weather generator. Paper under review in Journal of Hydrology.

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Online prediction tool for hydropower energy (Opt-HE)

Dr F. Jordan, Dr G. Artigue (Hydrique Engineers)
K. Cros, C.-A. Loetscher, O. Etter, Prof. Dr A. Schleiss (LCH-EPFL)
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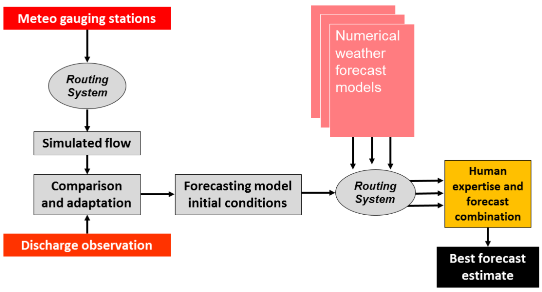
The OPT-HE project

OPT-HE : Optimal Prediction Tool for HydroElectricity

Hydrological prediction is a key factor in the optimization of hydropower production, by limiting the water spillings and increasing the water value. These objectives are perfectly in line with the *Energy Strategy 2050,* allowing an increase of the total electricity production with no new impact on the environment.
The partners of the project are five hydropower suppliers, MeteoSwiss and Hydrique Engineers.
The research is realized by Hydrique Engineers, the Laboratory of Hydraulic Constructions (EPFL) and the Institute for Climate and Atmosphere (ETHZ).

Structure of the project

The existing forecasting system at Hydrique Engineers is based on rainfall-runoff simulation, combining the assimilation of discharge gauging stations and human expertise. All these single processes are to be optimized within this project. Four workpackages are completed: general methodology, weather forecast, hydrological processes, operation.



Outcomes

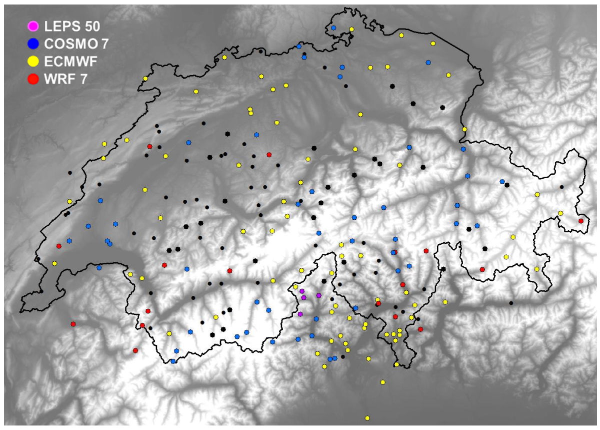
For this project, various tests have been realized, focusing on the specific characteristics of the catchment areas. As the existing system already had a satisfying performance, it was difficult to highlight improvements in the different methods showing a high performance. Out of the 18 different methods tested within the simulation and operation processes, 5 methods have been directly implemented. 3 additional methods, with less impact, have also been applied in the operational forecasting system at Hydrique.

Type of catchment area	Glacier	Prealpine	Jura-region	Added value
Temperature forecast bias	In operation			Very good
Analysis of the sources of forecast error		In operation	In operation	Very good
Influence of new precipitation stations			Rejected	Poor
Glacier model postprocessing with spline correction	In operation			Very good
Discharge assimilation in automatic correction	In operation	In operation	In operation	Very good
Uncertainty quantification and forecast	In operation	In operation	In operation	Very good
Combined glacier model with simulation and machine learning	In operation			Good
Assimilation of CombiPrecip data		Rejected	Rejected	Poor
Precipitation forecast quality assessement		In operation	In operation	Good
Pre-processing of stochastic weather forecast (COSMO-E)	In operation	In operation	In operation	Good
Seasonal forecasting	Rejected	In operation		Good
Precipitation forecast bias		Rejected	Rejected	Poor
Assimilation of COSMO-1 high-resolution forecast		In operation	In operation	Good
Use of COSMO-E instead of sensitivity method for the uncertainty prediction	Rejected	Rejected	Rejected	Poor
Short-term precipitation forecast by combination of observation and numerical weather forecast	Rejected	Rejected	Rejected	Poor
Post-processing of runoff forecasts using previous runs	Rejected	Rejected		Poor
Validation tests of the combined new methods	In operation	In operation	In operation	Very good
Inflow forecast by neural networks	Rejected	Rejected	Rejected	Poor
Influence of vegetation cover interception	Rejected	Rejected	Rejected	Poor

Intercomparison of meterological models

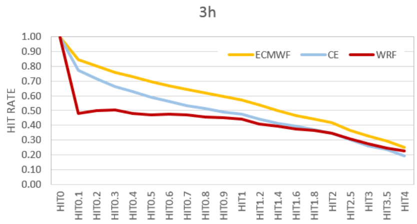
Weather models are the main inputs for hydrological forecast. Mainly precipitation and temperature forecast is of highest importance. In order to better choose the models during particular situations, it is crucial of knowing the real performance of the precipitation forecast.
A systematic performance analysis was realized over:

- 231 weather stations stations
- 5 different weather models
- 3 precipitation durations, 3 lead times (D, D1, D2). HIT* and FAR* rates for 20 intensity classes

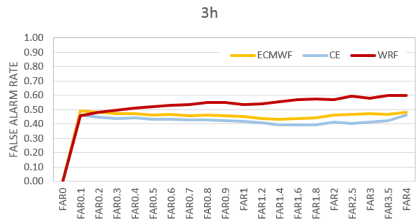


Best model for the HIT rate over 24 hours for a 24 mm threshold, D1

* the HIT rate indicate the success rate of a forecast. 1 is the best value (all observed events were predicted.
the FAR rate indicates the number of false alarms given by the model. 0 is the best value (no false alarm was produced by the model)



Comparison of HIT rates for 3 weather models and a 3 hours duration. Aggregation of all 231 weather stations.



Similar analysis but for FAR indicator. ECMWF produce the best results, in average, compared to cosmo-e and WRF.

	Indicator	JURA	PLATEAU	PREALPES	VALAIS	TESSIN	GRISONS
D	HIT 3h	CE	ECMWF	CE / WRF	ECMWF	CE / WRF	CE / WRF
D	HIT 24h	ALL		ALL	ECMWF	ALL	WRF
D	FAR 3h	CE	ECMWF / WRF	CE / ECMWF	ECMWF	CE	ALL
D	FAR 24h	CE	ECMWF / WRF	ECMWF	ECMWF	CE	ECMWF
D1	HIT 3h	CE / WRF	ECMWF / WRF	WRF	WRF	ALL	ALL
D1	HIT 24h	CE / WRF		CE / WRF	CE / WRF	ECMWF	
D1	FAR 3h	CE	CE / ECMWF	ECMWF	ECMWF	CE	ALL
D1	FAR 24h	ECMWF	ECMWF	ECMWF / WRF	ECMWF	CE	
D2	HIT 3h	ECMWF / WRF	ECMWF / WRF	WRF	ALL	ECMWF	CE / ECMWF
D2	HIT 24h	ECMWF		WRF	ECMWF	ECMWF	WRF
D2	FAR 3h	CE	CE / ECMWF	CE	ECMWF	CE / ECMWF	ECMWF
D2	FAR 24h		ECMWF	ECMWF	ECMWF	ECMWF	ECMWF

Regional summary of the “best model” for precipitation forecasting, according the the systematic analysis and result ponderation between HIT and FAR performance.

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Helicopter-borne ground-penetrating radar surveying of temperate Alpine glaciers

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For understanding the past, present and future change of glaciers, it is fundamentally important to gain knowledge about surface and subsurface glacier structures. Ground-penetrating radar (GPR) is an excellent method to investigate the thickness of glaciers. It was demonstrated in a PhD study (Lisbeth Langhammer, 2018), how traditional GPR methods can be advanced to survey Alpine glaciers more efficiently, and how the recorded data can be exploited to derive three-dimensional ice thickness maps. In the following, the three main thesis chapters are presented.

1. Ground-penetrating radar antenna orientation effects on temperate mountain glaciers

Extensive helicopter-borne and ground-based GPR investigations on the Glacier d'Otemma, Switzerland, demonstrated that the detectability of the ice-bedrock interface varies substantially with dipole orientation (Fig. 1). Dipole alignments parallel to the glacier flow generated considerable stronger and more coherent bedrock reflections than a perpendicular dipole setup. To help explain these findings, a 3D numerical modeling was perfomed using the open source software gprMax. The simulations indicated that the changes of the bedrock reflection amplitude are primarily governed by the bedrock topography. Scattering and intrinsic attenuation may also influence the amplitudes of the bedrock reflections, but these effects seem to be much less pronounced.

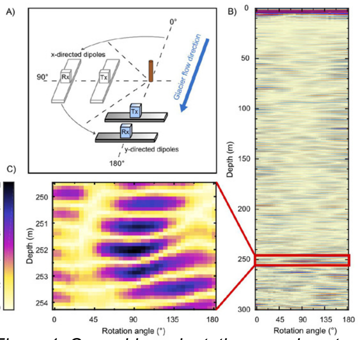

Figure 1: Ground-based rotation experiment. Antennas were rotated for 180° in 5° steps, starting with y-directed dipoles at 0° position. Bedrock reflection is at ~250m.

To increase the GPR bedrock reflection quality, antennas should be orientated parallel to the glacier flow direction on glaciers confined to a valley (Fig. 2). Since the directional dependence is a first-order effect, it is advisable to perform multi-component surveys, when the general shape of the bedrock topography is unknown.

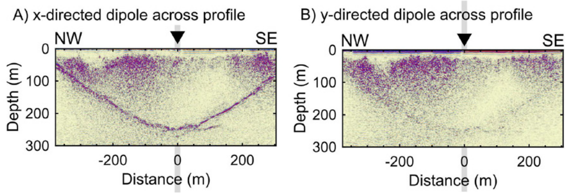

Figure 2: Comparison or ground-based pulseEKKO PRO 25-MHz Profiles

2. Glacier bed surveying with helicopter-borne dual-polarization ground-penetrating radar

Traditionally, helicopter-borne GPR systems are operated with a single pair of bistatic dipole antennas. It is demonstrated numerically that the directivity of the radiation pattern of single airborne dipoles (Fig. 3) does not correspond to an ideal full-space solution, if the antennas are employed at typical flight heights. These directionality effects can degrade the quality of the subsurface images significantly, when the GPR antennas are orientated unfavourably. Since an adjustment of the antenna orientation is impractical during flight, a novel dual-polarization helicopter-borne GPR system has been developed, consisting of two orthogonal pairs of commercial antennas in broadside configuration.

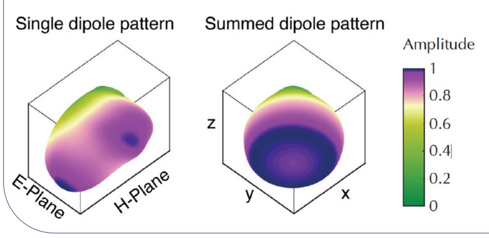

Figure 3: Single and summed interpolated 3D amplitude radiation pattern of an infinitesimal dipole placed 20 m above a half space interface (air - ice).

To overcome the image quality deficits of the individual channels, a pseudo-scalar approach was applied in which the data of both polarizations are combined. Results of helicopter-borne GPR surveys reveal more coherent bedrock reflections in the summed data compared to single dipole pair profiles (Fig. 4). Generally, the dual-polarization setup is more suitable than single antenna systems, because it is more versatile and less prone to directional effects caused by the placement of the dipole antennas in relation to undulating subsurface reflectors.

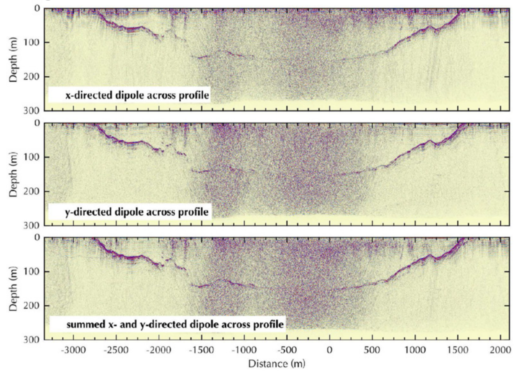

Figure 4: Profile from Plaine Morte Glacier with x-, y- and summed x- and y-directed dipoles.

3. Glacier thickness estimations and optimized survey design based on joint inversions of data and modeling constraints

The GlaTE inversion algorithm was developed to adequately invert for the 3-D ice thickness, based on physical modeling and observable data constraints. As an input, GPR-based bedrock reflection measurements are used to constrain the absolute thickness while the gradients of a mass conservation glaciological model are integrated to force the overall distribution. To account for parameter and data uncertainties, the constraints are formulated such that they can merged into a single set of equations and the thickness derived with the unconstrained glacier model is adjusted. The ice thickness e.g. of Morteratsch glacier is calculated successfully and improved in comparison to traditional mass conservation methods (Fig. 5). The GlaTE inversion is afterwards used to perform sequential optimized survey design for GPR campaigns in high mountain environments. It was found that for narrow valley-shaped glaciers, longitudinal profiles are generally sufficient, while wider saddle and convergence zone should be surveyed with additional across GPR profiles.

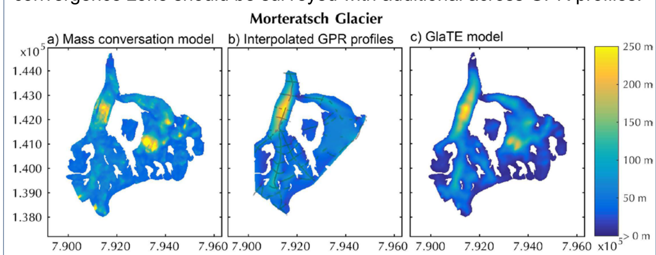

Figure 5: Comparison of glacier thickness estimations for the Morteratsch Glacier

Conclusion

The presented investigations and achieved results in this study substantially impact the field of ground-penetrating radar research on Alpine glaciers. With the novel helicopter-borne GPR acquisition unit, the optimized survey planning, advanced processing routines and the ice thickness estimation inversion, a complete set of tools has been developed to assess the glacier mass in the Swiss Alps and in other high-mountain regions.

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Reference: Langhammer, L., PhD Thesis "Helicopter-borne ground-penetrating radar surveying of temperate Alpine glaciers" (in preparation for final submission, successfully defended in August 2018)