# Task 2.4

## Title

Integrated simulation of systems operation

## Projects (presented on the following pages)

The role of pumped storage under current and future water availability and electricity prices
D. Anghileri, E. Weber, A. Castelletti, P. Burlando

Using streamflow forecasts to improve hydropower reservoir operations
D. Anghileri, S. Monhart, Z. Chuanyun, K. Bogner, A. Castelletti, P. Burlando, M. Zappa

Evaluation de l'effet d'une crue artificielle et de l'augmentation de sédiments sur la morphologie dans une rivière avec débit résiduel
A. Maître, S. Stähly, M. J. Franca, A. J. Schleiss

How does the HMID behave using numerical data?
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# The role of pumped storage under current and future water availability and electricity prices

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## Motivation

- European energy markets have experienced dramatic changes in the last years because of the massive introduction of Variable Renewable Sources (VRSs), such as wind and solar power sources, in the generation portfolios in many countries.
- This has resulted in lower electricity prices, but, at the same time, in increased price volatility, and in network stability issues.
- Storage hydropower systems play an important role in compensating production peaks, both in term of excess and shortage of energy.
- Hydropower systems are called to a more flexible operation to secure the supply and to maximize their income.

## Objectives and relevance of the work

- Assess how the operation of a pumped storage system react to different water availability scenarios (in terms of annual volume and seasonal pattern).
- Assess how the operation of a pumped storage system react to different electricity price scenarios (in terms of mean annual price and variance).

The results inform on the role of pumped storage systems under current and future climate conditions and electricity market situations.

## Approach

We use a modeling framework for the integrated continuous simulation of streamflow regimes and of operation of HP systems composed of:

- Mass balance model of the hydropower system (reservoir module of Topkapi-ETH).
- Design of the hydropower system operations using optimization techniques (optimal policy of the hydropower operations)
- Simulation of the optimal hydropower operations with a spatial distributed hydrological model (hydrological module of Topkapi-ETH)

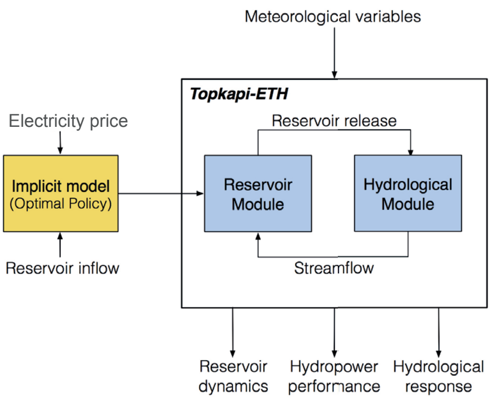
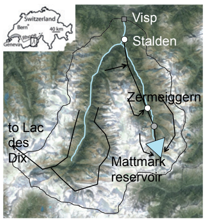



*Figure 1: Scheme of the modeling framework combining optimization of the hydropower operations (yellow box) and simulation of the combined- human-natural system (blue boxes).*

## Water availability and electricity price scenarios

| | Water availability | Electricity price |
|---|---|---|
| **Current scenario** | • Observed time series over the period 2008-2014. | • Observed time series over the period 2008-2014. |
| **Future scenario** | • Topkapi-ETH hydrological model<br>• Emission Scenarios: A1B<br>• Climate models: ECHAM5, RegCM3<br>• Stochastic Downscaling *(Bordoy Molina, 2013)* | • SWISSMOD model of the Swiss electricity market *(Schlecht and Weigt, 2014a,b)*<br>• Swiss Energy Strategy 2050 scenarios (Prognos, 2012)<br>• EU Energy Roadmap to 2050 (Capros 2013) |

## Study site




**Mattmark hydropower system**

Hydropower company: Kraftwerke Mattmark AG c/o Axpo Power AG

Mattmark storage: 100,101,000 $m^3$

Zermeiggern power plant: 38.8 MW

Zermeiggern pumping plant: 46 MW

Stalden power plant: 187 MW

Catchment area: 778 $km^2$

*Figure 2: Study site hydrological catchment and hydropower system.*

## Preliminary results

The optimal reservoir operating policy is designed by maximizing the hydropower income. While the release patterns remain similar when considering the 3 different price scenarios (showing increasing volatility because of increasing shares of VRSs), the pumping patterns vary significantly as a consequence of price volatility, showing an increase of both intensity and frequency (Figure 3).

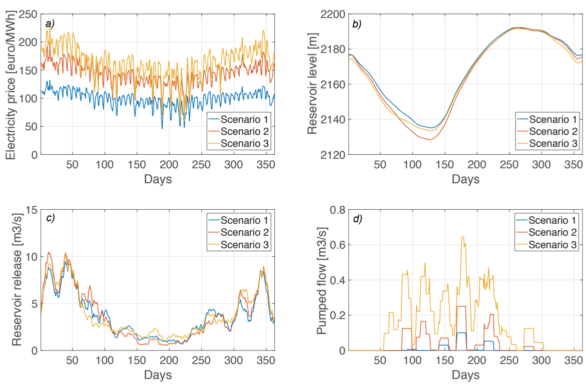



*Figure 3: a) Future price scenarios relative to 2025, 2035, and 2045 (Scenario 1-3 respectively): they correspond to different electricity market formulations with increasing shares of VRSs and increasing electricity demand. b-d) Reservoir storage, release, pumping (mean over 10 simulated years).*

### References

- Bordoy Molina (2013). Spatiotemporal downscaling of climate scenarios in regions of complex geography. PhD. Thesis – ETH Zurich.
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# Using streamflow forecasts to improve hydropower reservoir operations

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## Motivation

- Hydropower reservoir operation can be improved by considering streamflow forecasts when deciding how to operate the system, i.e., reservoir and power plant.
- Accurate and reliable streamflow forecasts are key to anticipate extreme events at different temporal scales, particularly on the short term (several hours ahead).
- Increased anticipation capability results into more flexible and adaptive hydropower operation over different time horizons from hourly operation, to weekly management, to monthly production planning.

## Objectives and relevance of the work

The objective of the work is to develop a real time hydropower operation system for Alpine snow and rain dominated system, which includes:

i. an ensemble streamflow forecasting system;

ii. a real-time control system scheme.

The specific objectives are:

- to analyze the quality of a set of streamflow forecasts on a retrospective dataset;
- to improve the hydropower system operations;
- to assess the utility of pre-processing meteorological forcing and post-processing streamflow forecasts in terms of hydropower performance.

The results inform on how much reservoir operations can benefit by the consideration of ensemble streamflow forecasts.

## Method and tools

We use a *forecast-based adaptive management framework* (see Figure 1) composed of:

### i) Forecasting system

The forecasting system used is the one developed and adopted in the NRP70 HEPS4POWER project. See separate poster by Monhart et al..

This system is a further development of the one used by Jörg-Hess et al. (2015) for early detection of hydrological droughts in Switzerland.

The new implementation has been setup for the Verzasca river basin and has following features:

- hydrological model PREVAH forced by monthly IFS ensemble predictions (5 members for 1994-2014 and 51 members for 2014-2015);
- use of raw and pre-processed IFS forcing. Pre-processing make use of quantile mapping;
- use of post-processing techniques to refine the streamflow forecasts (Bogner et al., 2016).

### ii) Real-time optimization system

We use a Model Predictive Control (MPC) scheme where the reservoir operations are periodically revised to include the most up-to-date streamflow forecasts.

We use a deterministic optimization on a rolling-horizon to define the operations for the following 30 days, we apply the reservoir release decision for the first day, and we re-optimize the operations for the following 30 days.

We repeat the optimization scheme for every forecast ensemble to estimate how the uncertainty in the forecasts translates into uncertainty in the reservoir operation performances. In so doing, we can assess how the buffering capacity of the reservoir can mitigate potential forecast inaccuracies.

## Experimental approach

The assessment of the improvement in HP system performances will be based on the framework proposed in Anghileri et al., (2016).

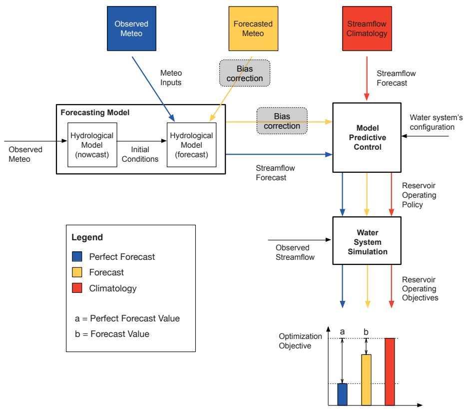


*Figure 1: Forecast-based adaptive management framework composed of a forecasting model and a Model Predictive Control optimization scheme. The experimental setting consists of two benchmark (perfect forecast, climatology) which are compared with the forecast to determine the improvement of the HP performances as measured by the reservoir operating objective (modified from Anghileri et al., 2016).*

## Study site

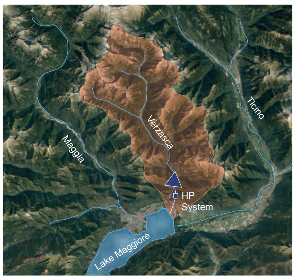


*Figure 2: Study area in red and Verzasca hydropower system.*

The forecast-based adaptive scheme is applied to the Verzasca hydropower system (Tessin).

<u>HP system features</u>

- Hydropower company: Verzasca SA
- Reservoir storage: 85 $10^6$ $m^3$
- Installed power: 105 MW

<u>Hydrological features</u>

The basin is characterized by mixed snow and rain.

At longer lead times the discrimination capability of hydrological predictions is better for low flow conditions (Figure 3). Only at early lead times higher flows show higher discriminative power. Predictions of flash floods remain challenging. The result confirms the findings by Jörg-Hess et al. (2015).

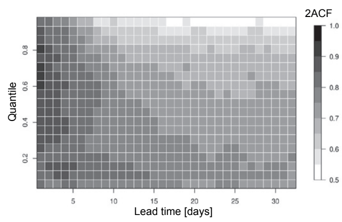


*Figure 3: Two-alternative forced choice score (2AFC) for different streamflow quantiles. Values below 0.5 indicate that the forecasts have no discrimination, a value of 1 indicates perfect discrimination.*

## References


- Anghileri, D., N. Voisin, A. Castelletti, F. Pianosi, B. Nijssen, and D. P. Lettenmaier (2016), Value of long-term streamflow forecasts to reservoir operations for water supply in snow-dominated river catchments, Water Resour. Res., 52, doi:10.1002/ 2015WR017864.
- Jörg-Hess S, Griessinger N and Zappa M. 2015. Probabilistic Forecasts of Snow Water Equivalent and Runoff in Mountainous Areas. J. Hydrometeor, 16, 2169–2186. doi: http://dx.doi.org/10.1175/JHM-D-14-0193.1
- Bogner K, Liechti K, Zappa M. 2016. Post-Processing of Stream Flows in Switzerland with an Emphasis on Low Flows and Floods. Water, 8(4), 115; doi:10.3390/w8040115

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# Evaluation de l'effet d'une crue artificielle et de l'augmentation de sédiments sur la morphologie dans une rivière avec débit résiduel

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## Contexte

Les barrages ont l'inconvénient de représenter une barrière à la continuité des cours d'eau. Le **régime de débit est modifié**, la **migration des poissons est interrompue** et les **sédiments sont retenus à l'amont des barrages**. La rivière de la Sarine a été considérablement modifiée par l'implantation en 1948 du barrage de Rossens. Le **déficit de charriage** à entrainé l'incision de la rivière et le développement d'une végétation importante qui stabilise les berges et empêche donc les sédiments d'être remobilisés. Après la modification de la LEaux en 2011, le canton de Fribourg a entrepris un programme de **renaturation** de la Sarine pour réduire les effets négatifs de l'utilisation de la force hydraulique.

## Solutions

Le canton de Fribourg et le groupe E, ont lâché une **crue artificielle de 24h** du 14 au 15 septembre 2016 pour nettoyer la rivière de ses algues. En parallèle, **des sédiments ont été ajoutés** par le LCH dans la rivière sous forme de **4 dépôts alternés**, selon (Battisacco, 2016).

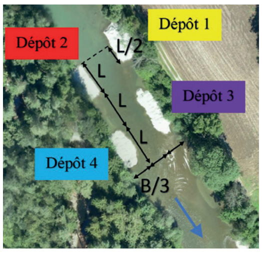
## Obectifs

Cette solution expérimentale vise à remobiliser les sédiments pour **réactiver une dynamique de charriage naturelle**. Une meilleure **diversité hydro-morphologique** de la rivière est attendue. Ceci devrait en outre, améliorer la qualité de vie des habitats pour la faune et la flore alluviales.

## Méthodologie

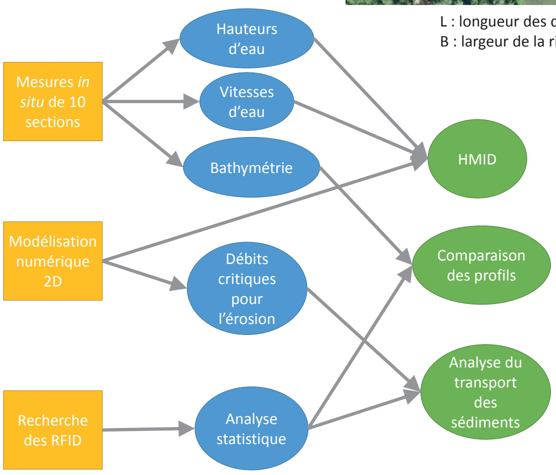
### Conditions initiales

- 4 dépôts de 250 m$^3$
- 489 sédiments équipés d'un système RFID (Radio Frequency Identification)
- Une crue artificielle pendant 24 h avec un débit de pointe Q = 195 m$^3$/s




L : longueur des dépôts
B : largeur de la rivière

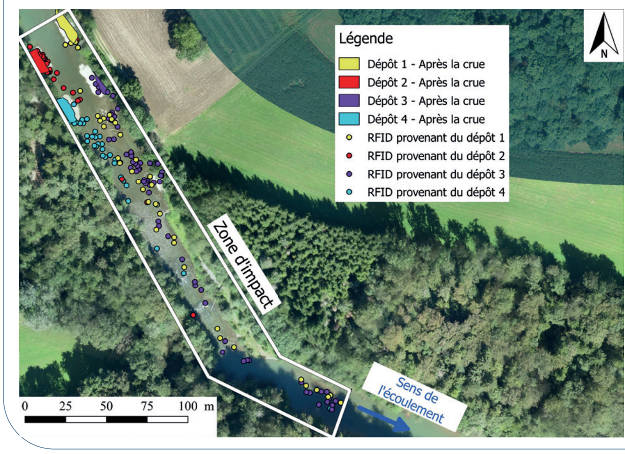
### Déroulement de l'étude




## Résultats

### Position des RFID et zone d'impact

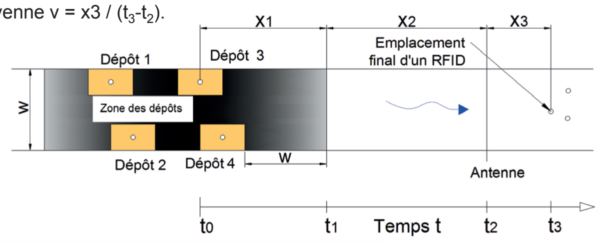
**277 RFID** retrouvés sur 489, dont 166 retrouvés dans la rivière et 111 sur les dépôts. La zone d'impact s'étale sur environ **300 m**.

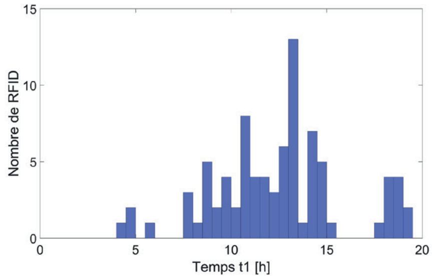



### Transport des RFID

Un RFID est mis en mouvement au temps $t_0$ puis sort de la zone des dépôts après un temps $t_1$. Il est ensuite détecté par une antenne au temps $t_2$ et finalement déposé après un temps $t_3$. Les débits critiques pour l'érosion, permettent de connaître $t_0$ et $t_3$.

Hypothèse: Les RFID parcourent la distance x2 + x3 à une vitesse moyenne $v = x3 / (t_3 - t_2)$.




**51 %** des RFID retrouvés dans la rivière ont été retrouvés en aval de la zone des dépôts. Le temps nécessaire $t_1$ qu'il leur est nécessaire pour sortir de la zone des dépôts est présenté ci-contre (à gauche).

### HMID (Indice hydro-morphologique de diversité)

**Amélioration plus importante (+30%) du HMID** dans la zone d'impact après la crue, suivant les mesures *in situ* et les résultats de la simulation numérique.

## Conclusion

Le HMID indique une **amélioration de la diversité hydro-morphologique** dans la zone d'impact, due aux dépôts.
Selon (Battisacco, 2016), un **nouvel ajout de sédiments** avec une crue pourrait augmenter considérablement la longueur de la zone d'impact.
Les dépôts **1 et 3 profitent de l'écoulement secondaire** créé par la courbe juste à l'amont et sont donc plus érodés. Plus de sédiments pourraient donc être ajoutés sur ce type de dépôts.
Bien que basé sur des hypothèses qui méritent une vérification plus approfondie, le temps $t_1$ élevé, nécessaire aux sédiments pour quitter la zone des dépôts, représente une **borne supérieure** et peut être **une valeur de comparaison de l'efficacité de la crue** pour de prochaines experiences.

## Références

Battisacco, E., Franca, M. J., & Schleiss, A. J. (2016). Sediment replenishment: Influence of the geometrical configuration on the morphological evolution of channel-bed. *Water Resources Research, 52*, 8879–8894

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# How does the HMID behave using numerical data?

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## Motivation

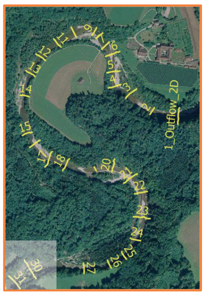
More than 15,000 km of the river network is categorized as strongly modified or artificial in Switzerland. In order to classify the natural state of a river, a solid method is needed. Commonly used methods, such as the Rapid Bio assessment Protocol (RBP, Barbour et al., 1999) based on **visual observations**, are sensitive to the person doing the survey.

The **Hydromorphological Index of Diversity** (short HMID, Gostner et al., 2013) can easily be combined with numerical 2D simulations and can serve as an **objective measure** in the geomorphological evaluation of a river before and after its modifications.

Based on a case study at the Sarine river, a **sensitivity analysis** of the HMID from numercial data was conducted, regarding:

- **Model calibration** (Strickler roughness values)
- **Extreme values**

## Case study Sarine




Situation of the Sarine
*Background: © swisstopo*

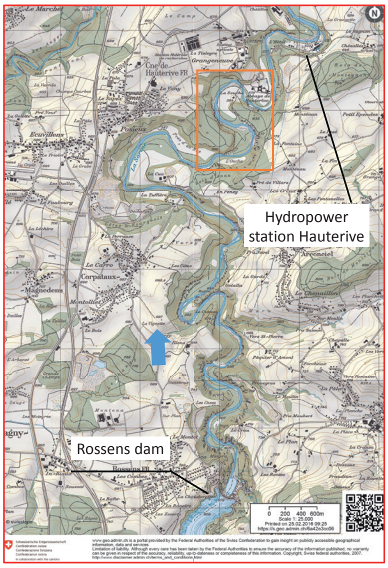



*Fig. 1: Situation (top left), Sarine river (right) and the cross-sections taken for the numerical 2D model (bottom left)*

**Sarine River (Figure 1)**
- Meandering river (wide canyon)
- Floodplain of national importance
- 2.5 $m^3$/s (residual flow reach)
- Average river width 30 m

**Numerical model**
- Numerical 2D model in BASEMENT with 2 m mesh size
- Based on 27 Cross-sections (80 m spacing) and LiDAR data

## Index

The HMID uses flow depth *h* and velocity *v* from different points in the river and is defined by Gostner et al. (2013) as :

$$HMID_{Site} = \prod_i (1 + CV_i)^2 = \left(1 + \frac{\sigma_h}{\mu_h}\right)^2 \cdot \left(1 + \frac{\sigma_v}{\mu_v}\right)^2$$

*CV* = coefficient of variation [-]
*μ* = mean value of flow depth [m] or velocity [m/s]
*σ* = standard deviation of flow depth [m] or velocity [m/s]

Classifying in three different groups:

| | |
|---|---|
| HMID < 3: | Channelized river with uniform cross-sections |
| 3 < HMID < 5: | Limited habitat variabilitly |
| HMID > 5 : | Full range of hydraulic habitats |

## Results model calibration

Based on the $d_{90}$ measured in the river, a initial Strickler roughness value *K* = 30.4 $m^{1/3}$/s was determined and applied. Table 1 shows that the optimal roughness based on the flow depth lies at *K* = 10 $m^{1/3}$/s.

Computing the HMID for the different roughness values one can observe in figure 2 that the HMID ranges from **8.4** (*K* = 10 $m^{1/3}$/s) to **12.1** (*K* = 30.4 $m^{1/3}$/s). The value measured with acoustic measurements in the field lies at 9.4 what was closest obtained with *K* = 14 $m^{1/3}$/s (HMID(K=14) = 9.6).

If the same procedure is applied with a higher discharge, the dependence is significantly smaller.

*Tab. 1: Calibration of Strickler roughness values and the difference in water levels compared to the in-stream measured*

| K [$m^{1/3}$/s] | MAX DIFFERENCE [m] | MEAN DIFFERENCE [m] |
|---|---|---|
| **30.4** | 0.45 | 0.20 |
| **28** | 0.45 | 0.19 |
| **16** | 0.41 | 0.12 |
| **14** | 0.39 | 0.11 |
| **12** | 0.38 | 0.09 |
| **10** | 0.35 | 0.09 |

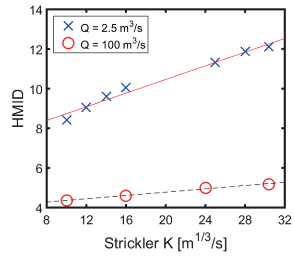



*Fig. 2: Dependence of HMID on Strickkler roughness value*

## Results extreme values

Taking the example of *K* = 10 $m^{1/3}$/s, the influence of extreme values was investigated. The blue lines in figure 3 show the removal of the largest and the smallest 5% of the values. The HMID drops from 8.4 to **5.6**, what corresponds to a **decrease of 33%**.

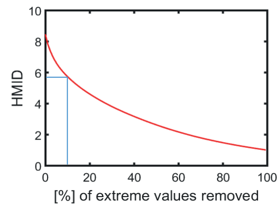



*Fig. 3: Dependence of HMID on extreme values*

## Discussion and conclusion

- Analysis have shown that the calibration of a nurmerical model is important in regards to HMID computations. This effect is stronger at low discharges. In the Sarine the not calibrated model attains an HMID which is roughly **30% higher** than the best calibrated.
- A well calibrated model attains HMID values which are close to the one measured in the field.
- The HMID is largely influenced by extreme values. Therefore, data selection in the field has to ensure that **profiles with shallow as well as profound flow depths are accurately represented in the dataset**!
- In this analysis, the Manning-Strickler flow law was applied, which has been developed for uniform flow and giving one average flow velocity within a profile. Numerical 2D models are more complex and may be more accurate using different flow laws. **The study wants to bring the HMID closer to planning engineers who often use the Manning-Strickler approach.**

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Barbour, M. T., Gerritsen, J., Snyder, B. D., & Stribling, J. B. (1999). *Rapid bioassessment protocols for use in streams and wadeable rivers: periphyton, benthic macroinvertebrates and fish* (2nd ed., p. 339). Washington, DC: US Environmental Protection Agency, Office of Water.

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