Intervention strategies to mitigate hydropeaking: Two case studies from Switzerland

M. Bieri, B. Zünd, M. Gasser
Pöyry Switzerland Ltd.
Herostrasse 12, PO Box 555
8048 Zurich
Switzerland

A.J. Schleiss
EPFL
Laboratory of Hydraulic Constructions
1015 Lausanne
Switzerland

Water retention in reservoirs and concentrated turbine operations allow electricity to be produced on demand. Sudden opening and closing of the turbines can produce highly unsteady flow conditions in the river downstream of the tailrace channel, the so-called hydropeaking. Mitigating its adverse impacts on the aquatic ecosystems has become a mandatory requirement in today's water policies in many countries. Existing facilities are being 'rehabilitated' for habitat improvement or restoration, and new facilities designed with a focus on habitat conservation. However, there are regions still suffering from a lack of experience in respect of hydropower-related ecological challenges and little scientific knowledge available on local ecosystems. The paper presents two selected projects of hydropeaking mitigation in Switzerland: the Mauvoisin II scheme extension according to project specific design guidelines and the Plessur hydropower scheme according to today's mitigation policy. For both projects the context, the evaluation procedure as well as the findings are given and compared, covering a wide range of feasible solutions. Understanding the specific behaviour of local species is the starting point in order to address the unique needs for each and every project. However, the approach how to define the best performing intervention strategy can be defined and will be presented in the paper, considering the lessons learnt from hydropeaking mitigation projects.

1. Background

High-head storage hydropower plants (HPP) contribute significantly to peak energy production as well as electricity grid regulation. Water retention in reservoirs and concentrated turbine operations allow electricity to be produced on demand. In Switzerland, for example, 32% of the total electricity in 2010 was produced by storage hydropower plants. Sudden opening and closing of the turbines produce highly unsteady flow conditions in the river downstream of the tailrace channel (Moog 1993). This so-called hydropeaking is the major hydrological alteration in Alpine regions (Petts 1984, Poff et al. 1997). Due to the unpredictability and intensity of flow change, sub-daily hydropeaking events disturb the natural discharge regime, a key factor in ecological quality and the natural abiotic structure of ecosystems (Parasiewicz et al. 1998, Bunn and Arthington 2002). These disturbances directly affect riverine biological communities (Young et al. 2011). Frequent and rapid fluctuations change hydraulic parameters, such as flow depth, velocity, bed shear stress and temperature, e.g. as shown for the Moesa river in Switzerland in Fig. 1, and thus influence habitat availability, stability and quality.

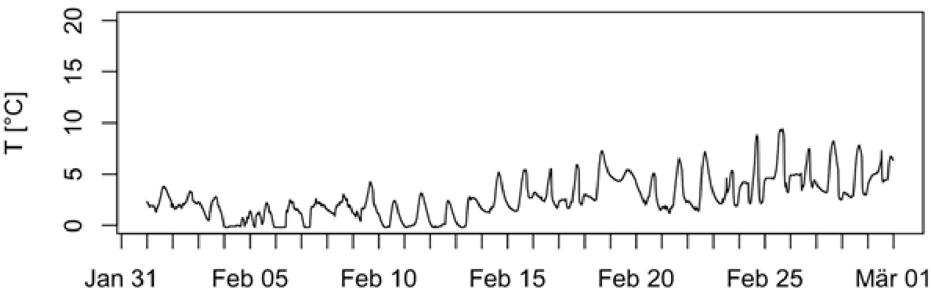

Fig. 1. Water temperature of hydropeaking impacted Moesa river donstream of Soazza HPP in February 2012.

Mitigating the adverse impacts on the aquatic ecosystems is a mandatory requirement in today's water policies. After decades of extensive use of water resources with some severe consequences for aquatic and riverine biota, the government and the administration are starting to recognize the need of a water protection policy, e.g. the European Union's Water Framework Directive (WFD 2002). Several countries set environmental standards for water. In Switzerland, the Parliament adapted the Law on Water Protection in 2009 to improve the quality of Swiss waters, including hydropeaking mitigation. To cover the cost of the hydropeaking mitigation measures, an annual amount of CHF 50 million is available. This money feeds a fund for full compensation of rehabilitation costs undertaken by HPP operators. The river restoration measures have to be realized in the next 20 years.

2. Method

Hydropeaking mitigation measures include:

- **Operational measures**: The operation schedule of a plant can be modified for specific ecological requirements. This should be achieved without major production losses.
- **Construction measures**: A compensation basin or cavern downstream of turbine release, a powerhouse outflow deviation or morphological improvements of the river are technical measures to cope with hydropeaking without impacting plant operation.

For all projects, understanding the specific behaviour of local species is the starting point in order to address the unique needs for each and every project. However, the approach how to define the best performing intervention strategy can be defined, as shown in Fig. 2:

- **Monitoring and data acquisition:** The reference state needs to be documented, and the deficits of the ecosystem have to be defined by appropriate indicators (e.g. flow velocity, sediment, temperature). Beside the analysis of historic data series, hydraulic modelling, field investigations, or expert involvement might be requested.
- **Potential operational and construction measures:** Once the impact has been qualitatively and quantitatively (indicators) addressed, measures need to be developed to compensate the deficit. Potential mitigation measures should always focus on the target and threshold values (e.g. flow ramping rate) defined. If a measure only improves the situation without reaching the set targets, it does not account for a mitigation measure (e.g. reducing the flow ramping without achieving the target to avoid fish stranding).
- **Comparison and decision-making:** The impact of the mitigation measures needs to be compared to the reference stage. Measures achieving the mitigation target should be compared considering economic (construction cost and time), environmental (land use, disposal etc.) and social (relocation, agriculture, etc.) criteria. Several decision-making approaches are known and can be applied for the selection of the appropriate mitigation measure.
- **Design, implementation and commissioning:** Once a mitigation measure has been chosen, it has to undergo the common process of realisation. Well defined design criteria, especially focusing on the hydropeaking mitigation relevant aspects, streamline the design and implementation process. Potential adjustments should be included in the design (e.g. potential increase of release capacity).
- **Performance review and adjustment:** Once the measure is under operation, its performance needs to be approved. The same or similar approaches as applied for the deficit analysis should be applied for the performance review. If the results do not show the expected performance, adjustments might be needed. This is an ongoing activity and the process repeats during the lifespan of the hydropower project.

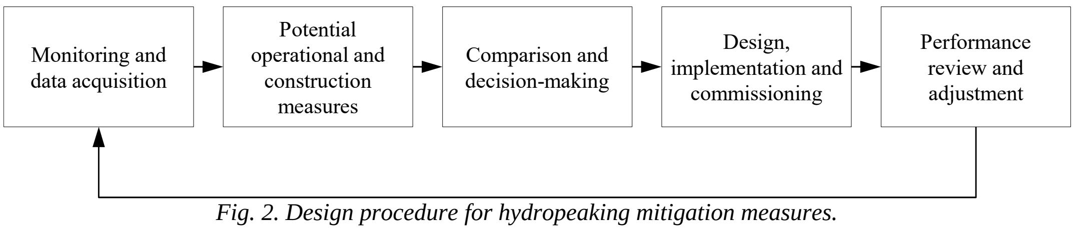

Fig. 2. Design procedure for hydropeaking mitigation measures.

3. Case studies

In Switzerland, legal guidelines for hydropeaking mitigation are new. Authorities, powerplant owners and designers as well as the NGOs need to become familiar with the given conditions. A first project in the Swiss Alps on the Hasliaare river has been implemented (Bieri et al. 2014, Person et al. 2014). However, the need for attenuation of up- and downsurge is not an entirely new subject, besides ecology power peaking can have adverse effects in many fields, such as irrigation systems or navigation. An example is the Randenigala-Rantembe hydropower scheme on the Mahaweli Ganga in Sri Lanka, set into operation in 1986. The 90 m high Randenigala dam, storing almost 900 million m^3, has a plant factor in the range of 0.4, the same as the smaller Rantembe stage which follows just downstream. Resulting fluctuations can be too high for the downstream irrigation schemes. Thus, the live storage of Rantembe has been designed allowing flow regulation.

3.1. Mauvoisin II project, Canton of Valais, Switzerland

When in the 90s on the discussion on residual water issue was being settled in Switzerland, the mitigation of hydropeaking also became subject of public discussion. One of the first projects confronted with this issue was Mauvoisin II, a power increase project in the Canton of Valais in the southwestern area of Switzerland. Despite the project being cancelled in the end, the planning had achieved all requirements for construction, including the consent of the environmental organizations, and represents the state of the art without government impose guiding principles.

The existing scheme went into operation in 1956 and 1958. The main element is the 252 m high Mauvoisin arch dam at an elevation of 1,975 m asl, storing 200 million m^3 of water. Besides the smaller upstream stage Chanrion, the water is used by two principal stages, Fionnay and Riddes, and then restituted to the Rhone river, as shown in Fig. 3. The rated capacity of the two power plants is 128 and 225 MW, respectively. The rated discharge is 34.5 m^3/s for Fionnay, but only 29 m^3/s for Riddes. The combined operation required a compensation pond at Fionnay.

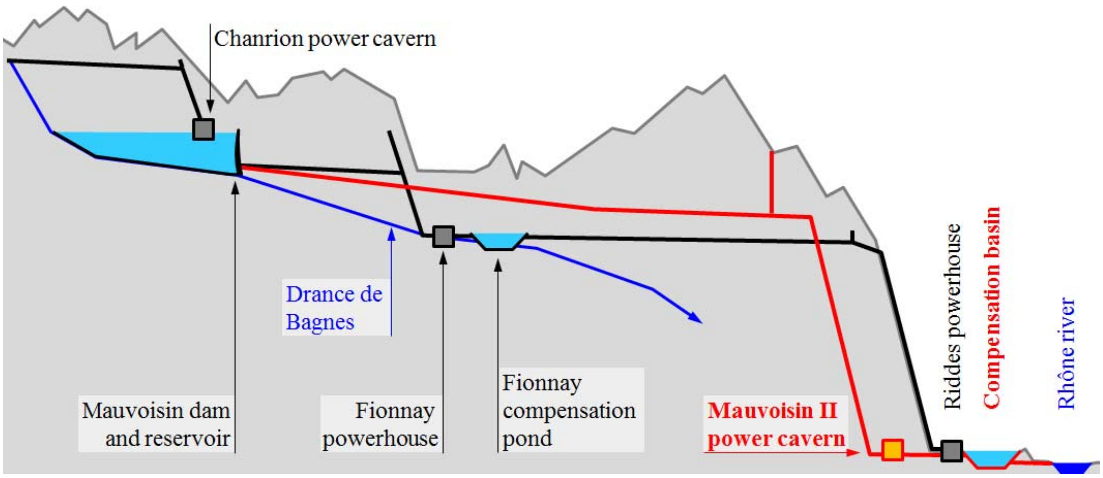

Fig. 3. Longitudinal profile of Mauvoisin scheme. Black: existing; red: Mauvoisin II project.

Just a few years before the project development of Mauvoisin II, Mauvoisin dam had been elevated by another 13.5 m, increasing the storage capacity by 20 million m^3. The next step was to be an increase of the power output from 350 MW to 900 MW. The goal was not just to increase the peak output, but also to obtain better operational conditions. Thus, a parallel single stage was foreseen from the reservoir down to a new power cavern just nearby the old Riddes power station, with a gross head of 1,500 m. The total cost estimate was at CHF 650 million.

Despite the size of the project, its remaining environmental impact was predicted to be modest since most parts were underground. The main issues were excavation disposals and the transient phenomena in the Rhone river. The maximum release would have risen from 29 m^3/s to 75 m^3/s, i.e. by 160%. Just for comparison, the mean annual flow of the Rhone river upstream of Riddes is about 110 m^3/s, and in January and February even around 40 m^3/s.

Thus, as a proactive measure a compensation basin with a volume of 470,000 m^3 was included in the project, occupying an area of about 100,000 m^2. Both the existing Riddes units as well as the new Mauvoisin II units would restitute their water into the basin, from where it would be released through a regulation gate and two culverts – the existing and a new one – into Rhone river.

Fig. 4 shows a hydrograph for a typical winter week day (black curve) for existing conditions: The variations – not just due to the existing Riddes power station but also including further upstream power schemes and the natural glacier melt oscillation – can be in the range of 100 m^3/s. Together with the new Mauvoisin II scheme these peaks would have increased by another 40 to 50 m^3/s, with production periods concentrated from 10 to 12 hours to 4 to 5 hours. For such small peaking periods, the compensation basin would have stored sufficient water to attenuate the surge in the river almost to the level without Mauvoisin II implementation. The stored water would then have been released during the night in order to increase the low flows. For longer turbine periods the attenuation of the peaks was less, but the basin could still be used to reduce the gradients of the hydrograph. The Mauvoisin II hydropeaking project would have improved the transient conditions in the river.

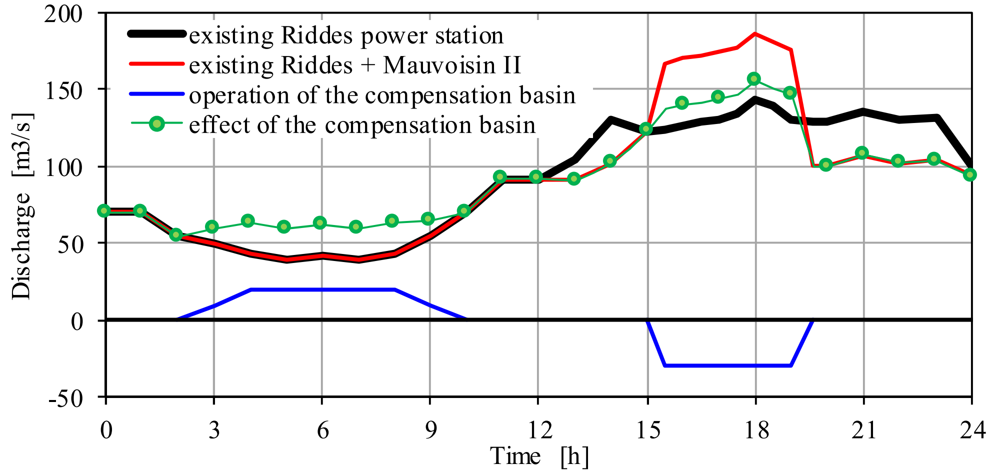

Fig. 4. Theoretical operation of the compensation basin in a winter working day.

Although representing the main ecological investment of the project, the compensation basin was also an ecological issue, as it would have been the most visible element of the project. Beside impacts on vegetation and fauna, landscape issues had to be addressed due to the surrounding dam of about 9 to 10 m height. Much care was given on the integration into the landscape by covering the slopes with adequate vegetation, as shown in Fig. 5.

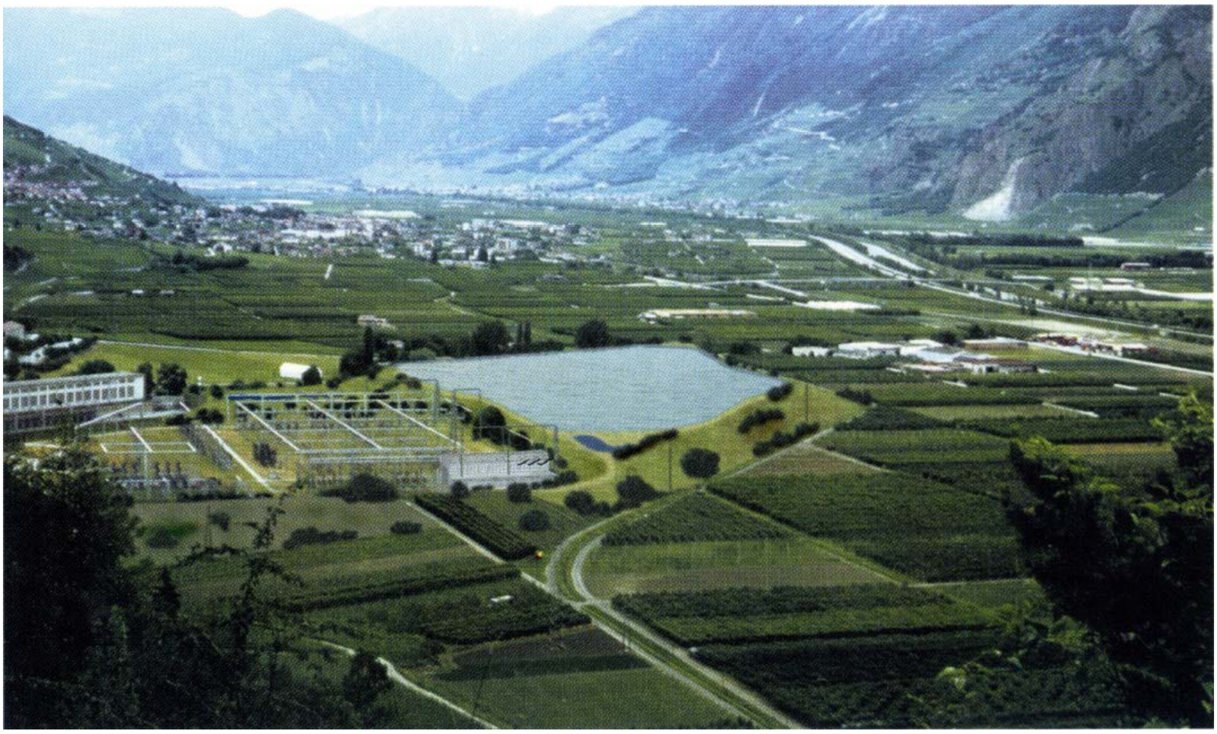

Fig. 5. 3D view of the intended compensation basin. Note the existing Riddes power station at the right hand side and the culverts connecting the scheme to the Rhone river on the left hand side.

3.2. Plessur project, Canton of Graubünden, Switzerland

The Plessur river in the Schanfigg valley between Arosa and Chur in eastern Switzerland is operated by a cascade of three hydropower plants. The 4.7 MW Litzirüti HPP located upstream (including Isel dam and reservoir of about 300'000 m^3 storage) and the 8.8 MW Chur-Sand HPP downstream have been recently rehabilitated and reliably produce energy for the local power grid. As shown in Fig. 6, the 6.7 MW Lüen HPP is located between the two plants. This power facility, consisting of a 10 m high weir with a lateral intake, a 2.5 km long power tunnel, a 700 m penstock and a powerhouse with three generating units, was commissioned in 1914. Despite several refurbishments over the last decades, the hydropower scheme needs an extensive rehabilitation. A layout with a considerably smaller river intake, providing space for environmental recreation of the now completely silted-up storage area has been developed in the framework of a recent feasibility study, including upstream and downstream fish migration facilities. The river reach between Litzirüti HPP and Lüen HPP has not been exploited yet.

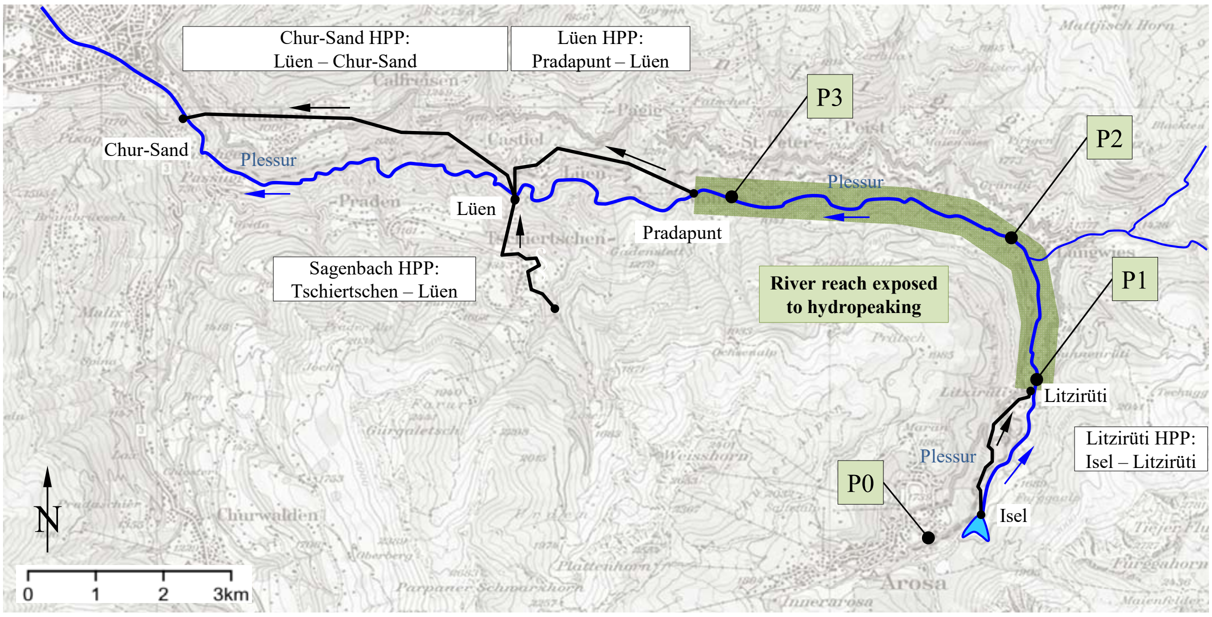

Fig. 6. Schanfigg Valley with actual layout of the hydropower plants and the control sections for the ecological assessment

A major environmental concern is the flow regime of the Plessur river suffering from unsteady flow releases from the Litzirüti storage HPP. The ecological evaluation of the current situation was based on biotic and abiotic indicators proposed by the guidelines imposed by the Swiss federal administration (Baumann et al. 2012). The value of each individual indicator was linked to a range of five ecological quality classes: (1) very good, (2) good, (3) moderate, (4) unsatisfactory and (5) poor, being comparable to classes of the assessment guidelines of the European Water Framework Directive (WFD 2000). Evaluation of each indicator was performed for the reference (P0) as well as the three (P1, P2, P3) hydropeaking reaches (ANU 2014).The ecological analysis came to the conclusion that the Litzirüti HPP generates highly unsuitable conditions in the Plessur river reaches downstream of the turbine release. As shown in Tab. 1, especially "Substrate Clogging" (S1), "Minimum Discharge" (D1) as well as "Fish Stranding" (F2) and "Fish Reproduction" (F4) have been found to majorly impacted by hydropeaking. Thus, the local authorities ordered the Plessur river flow conditions to be mitigated by appropriate measures.

A thorough analysis showed that a retention volume of about 30'000 m^3 would be requested to mitigate the negative impacts of hydropeaking for the relevant river sections. This volume would have to be implemented between the tailrace of the Litzirüti HPP turbine and the Plessur river. As the Litzirüti HPP is used to generate demand-driven, operational measures were excluded. The following potential construction measures were evaluated:

- **Compensation basin** could be built either on the left or the right side of the river in the valley at Litzirüti. Such a facility would occupy considerable surface. Beside the construction cost of more than CHF 15 million, high indirect costs were expected to compensate the agricultural and ecological loss.
- **Compensation cavern** could be excavated in the mountain massif close to the Litzirüti powerhouse. Thus, surface impact could be reduced to a minimum. Disadvantages of such a concept were the relatively high cost of more than CHF 25 million as well as the spoiling of the excavation material.

- **Powerhouse outflow deviation** could be achieved by a new hydropower scheme, connecting the tailrace channel of the Litzirüti HPP to the headrace channel of the further downstream located Lüen HPP. Thus electricity production could be increased and hydropeaking in the river avoided.

Tab. 1. Ecological evaluation of the hydropeaking section of the Plessur river applying biotic and abiotic indicators (ANU 2014).

Control Section	Ecomorphology	Fish Stranding (F2)	Fish Spawning Grounds (F3)	Fish Reproduction (F4)	Fish Productivity (F5)	Macroinvertebrate Biomass (M1)	Macroinvertebrate Diversity (M2)	Longitudinal zonation of macroinvertebrates (M3)	Substrate clogging (S1)	Minimum discharge (D1)	Water Temperature (T1)	Overall Impact
P0 (Ref.)	3	0	0	0	0	1	2	4	0	1	0	2
P1	1	5	0	5	1	1	2	4	5	5	1	5
P2	1	2	0	5	1	1	2	3	4	0	0	0
P3	1	0	0	5	1	1	2	3	4	0	0	0

Ecological quality classes:

1	Very good
2	Good
3	Moderate
4	Unsatisfactory
5	Poor
0	Not considered

After comparison of the economic, environmental and social impact of the three alternative concepts, the decision was made to avoid the cost intensive reservoir or underground facility and develop the Pradapunt HPP on the river reach between Litzirüti HPP and Lüen HPP, providing a net head of 400 m. In the developed design of the new Pradapunt HPP the tailwater of the Litzirüti HPP would be transferred to the 1,830 m long headrace tunnel, as shown in Fig. 7. The tunnel provides storage volume to compensate for the unsteady water releases. A steel-lined penstock leads the water to the powerhouse in Pradapunt, containing the Pelton power unit of 10 MW installed capacity. The tailwater is directly injected into the headrace tunnel of Lüen HPP. The developed concept allows an increase of electricity production, minimizing construction and maintenance costs, providing best spatial integration and mitigating the negative impacts on the environment of the existing facilities. The project has been developed to feasibility stage for concession agreement, power purchase as well as subsidies (from hydropeaking mitigation fund) discussions.

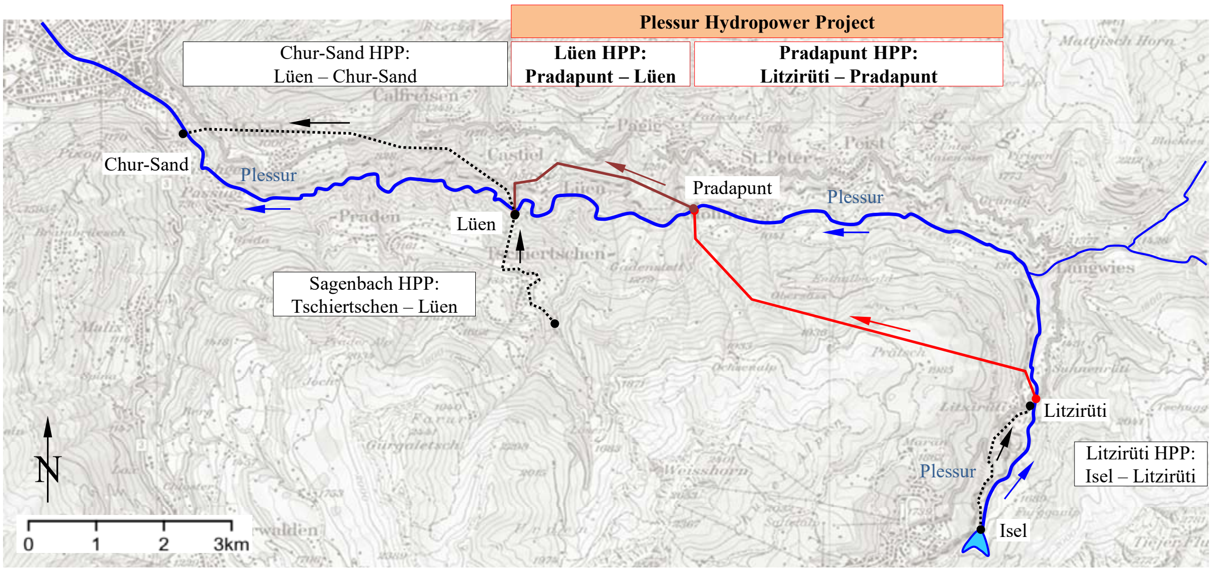

Fig. 7. Schanfigg Valley with the hydropower plants including the upgraded Lüen HPP and the new Pradapunt HPP

Conclusion

Demand-driven hydropower operation can result in unsteady water releases to rivers, altering the natural flow regime. This can diminish the biomass and richness of species, including fish at several life stages and therefore mitigating the adverse impacts on the aquatic ecosystems is a mandatory requirement in today's water policies as well as being best practice. Operational measures requesting a modified plant operation schedule can be for specific ecological requirements, which should be achieved without major production losses. Construction measures, such as a compensation basin or cavern downstream of turbine release, a powerhouse outflow deviation or morphological improvements of the riverbed can often cope with hydropeaking without impacting plant operation.

After decades of intensive use of water resources, many governments have implement water protection policies through legal frameworks such as the European Union Water Framework Directive. This has had a mobilising effect on parts of the industry. Several schemes are being transformed in order to meet stringent environmental requirements, as shown for the Plessur scheme. Existing facilities are being 'rehabilitated' for habitat improvement or restoration, and new facilities designed with a focus on habitat conservation according to stringent guiding principles, e.g. imposed by the Swiss federal administration (Baumann et al. 2012). Nevertheless, already in the past project specific approaches have been developed to address hydropeaking, as for the Mauvoisin II scheme.

However, there are regions still suffering from a lack of experience in respect to hydropower-related ecological challenges and little scientific knowledge available on local ecosystems. Even if the type of design constraints are similar to common projects in developed areas, their magnitude is often much higher. Key constraints for hydropeaking mitigation design in undeveloped areas include large biodiversity as well as large biomass rate.

The five steps presented in Fig. 2 cover the span of a hydropeaking mitigation project. To begin with it is essential to have monitoring and data acquisition in place at the pre-build stage to ensure the 'default' wildlife behavior and balance is logged. This will then inform pre-build decision making that will involve drawing comparisons and commissioning the build to realise the most appropriate design. Finally, there must be ongoing performance review and adjustment based on effects caused through operations. This is an ongoing activity and the process is repeated during the lifespan of the hydropower project. Every HPP is unique so best practice is not to apply the same design, but to apply the same guiding principles.

References

1. **ANU**, „Strategische Planung Sanierung Schwall und Sunk: Defizitanalyse, Massnahmenplanung", Amt für Natur und Umwelt, Kanton Graubünden, Chur, 2014.
2. **Baumann, P., Kirchhofer, A., Schälchli, U.**, „Sanierung Schwall/Sunk - Strategische Planung. Ein Modul der Vollzugshilfe Renaturierung der Gewässer", *Umwelt-Vollzug 1203*, Bundesamt für Umwelt, Bern, 2012.
3. **Bieri, M., Müller, M., Schweizer, S. and Schleiss, A.,** "Flow restoration in Alpine streams affected by hydropower operations—a case study for a compensation basin", *Proceedings of River Flow 2014*, Special Session on Swiss Competences in River Engineering and Restoration: 181-190, 2014.
4. **Bunn, S.E. and Arthington, A.H.,** "Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity", *Environmental Management* 30(4): 492-507, 2002.
5. **Moog, O.,** "Quantification of daily peak hydropower effects on aquatic fauna and management to minimize environmental impacts*". Regulated Rivers: Research & Management* 8(1-2): 5-14, 1993.
6. **Parasiewicz, P., Schmutz, S. & Moog, O.,** "The effect of managed hydropower peaking on the physical habitat, benthos and fish fauna in the river Bregenzerach in Austria", *Fisheries Management and Ecology* 5: 403-417, 1998.
7. **Person, E.; Bieri, M.; Peter, A. and Schleiss, A.,** "Mitigation measures for fish habitat improvement in Alpine rivers affected by hydropower operations", *Ecohydrology* 7 : 580-599, 2014.
8. **Petts, G.E.,** "Impounded rivers", Wiley, Chichester, UK, 1984.
9. **Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E. and Stromberg, J.C.,** "The natural flow regime", *BioScience* 47(11): 769-784, 1997.
10. **WFD,** "Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy", *Official Journal of the European Communities L327*, 2000.
11. **Young, P., Cech, J. and Thompson, L.,** "Hydropower-related pulsed-flow impacts on stream fishes: A brief review, conceptual model, knowledge gaps and research needs", *Reviews in Fish Biology and Fisheries* 21(4): 713-731, 2011.

The Authors

Dr Martin Bieri has eight years of experience in hydrologic and hydraulic engineering. Before joining Pöyry in 2012, he worked as a research associate at the Laboratory of Hydraulic Constructions (LCH) at the École Polytechnique Fédérale de Lausanne (EPFL), Switzerland, where he did a PhD on the operation of complex hydropower schemes and the impact on the flow regime in the downstream river system. Besides he was involved in teaching as well as many applied research projects, numerical simulations for flood retention, climate change, hydropower management and ecological flow concerns among others. He obtained his Master's degree in Civil Engineering at EPFL in 2007. Besides other projects, Martin Bieri is working as a project manager for hydropower projects in South-East Asia. He is member of the steering committee of the Swiss Society of Hydrology and Limnology.

Dr Benno Zuend holds a MSc and a PhD in Civil Engineering at ETH Zurich. He has 15 years of professional experience at Pöyry Switzerland and the predecessor company Electrowatt Engineering. During his PhD he was teaching at ETH Zurich and at the technical high school of Winterthur. His doctoral thesis investigated the impact of the air concentration of the flow velocity and identified the mechanism behind this phenomenon. He is a Senior Engineer in Hydraulic Engineering. His fields are water power hydraulics and flood protection. Recent work includes the assessment of the hydraulic safety of nine dams in Malaysia and of three large weirs in Switzerland, the development of an energy dissipater in very restricted space conditions, the design of a capacity increase of the river Limmat within city area, or the design of an underground flow separation device which is crucial for flood safety of a large Swiss town, supported by 3D calculations.

Dr. Max Gasser holds a MSc and a PhD in Biology at ETH Zurich. He has 26 years of professional experience at Pöyry Switzerland and the predecessor company Electrowatt Engineering. He is a Senior Engineer in the Environmental Department. His fields are environmental impact assessments as well as realization and monitoring of compensation measures in the framework of infrastructure projects.

Prof. Dr Anton J. Schleiss graduated in Civil Engineering from the Swiss Federal Institute of Technology (ETH) in Zurich, Switzerland, in 1978. After joining the Laboratory of Hydraulic, Hydrology and Glaciology at ETH as a research associate and senior assistant, he obtained a Doctorate of Technical Sciences on the topic of pressure tunnel design in 1986. After that he worked for 11 years for Electrowatt Engineering Ltd. in Zurich and was involved in the design of many hydropower projects around the world as an expert on hydraulic engineering and underground waterways. Until 1996 he was Head of the Hydraulic Structures Section in the Hydropower Department at Electrowatt. In 1997 he was nominated full professor and became Director of the Laboratory of Hydraulic Constructions (LCH) in the Civil Engineering Department of the Ecole Polytechnique Fédérale de Lausanne (EPFL). The LCH activities comprise education, research and services in the field of both fundamental and applied hydraulics and design of hydraulic structures and schemes. The research focuses on the interaction between water, sediment-rock, air and hydraulic structures as well as associated environmental issues and involves both numerical and physical modelling. Actually 19 Ph.D. projects are ongoing at LCH under his guidance. Prof. Schleiss is also involved as an international expert in several dam and hydropower plant projects all over the world as well as flood protection projects mainly in Switzerland. From 2006 to 2012 he was Director of the Civil Engineering program of EPFL and chairman of the Swiss Committee on Dams (SwissCOLD). In 2006 he obtained the ASCE Karl Emil Hilgard Hydraulic Price as well as the J. C. Stevens Award. He was listed in 2011 among the 20 international personalities that "have made the biggest difference to the sector Water Power & Dam Construction over the last 10 years". 2014 he became also Council member of International Association for Hydro-Environment Engineering and Research (IAHR) and chair of the Europe Regional Division of IAHR. For his outstanding contributions to advance the art and science of hydraulic structures engineering he obtained in 2015 the ASCE-EWRI Hydraulic Structures Medal. After having served as vice-president between 2012 and 2015 he was elected president of the International Commission on Large Dams (ICOLD) in 2015.