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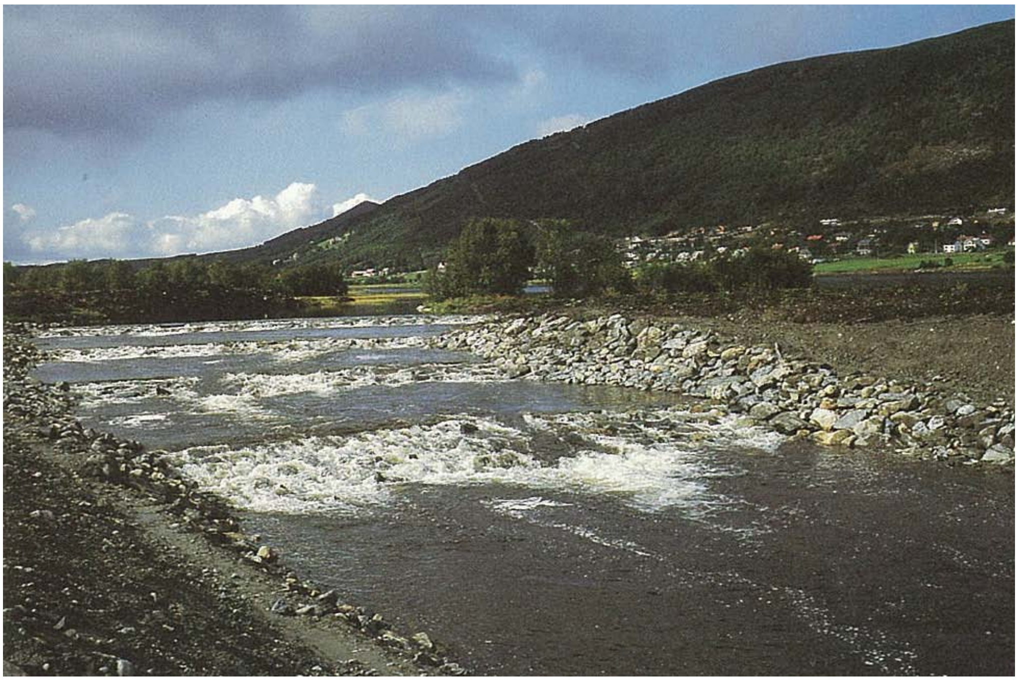
Report

Mitigation Measures Against Hydropeaking Effects

A literature review

Author(s)
Julie Charmasson
Peggy Zinke



CEDREN Centre for Environmental Design of Renewable Energy

SINTEF Energy Research
Energy Systems
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SINTEF Energi AS
SINTEF Energy Research

Address:
Postboks 4761 Sluppen
NO-7465 Trondheim
NORWAY

Telephone:+47 73597200
Telefax:+47

energy.research@sintef.no
www.sintef.no/energi
Enterprise /VAT No:
NO 939 350 675 MVA

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AUTHOR(S)
Julie Charmasson
Peggy Zinke

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ABSTRACT
Hydropeaking consists of variations in discharge and water level due to releases of water retained in storage basin to generate electricity according to the market demand. These unnatural flow fluctuations create frequent and rapid variations in terms of flow magnitude, flow velocity, water depth, water temperature, wetted area and sediment transport which also can affect channel morphology. Such changes may lead to degradation of physical conditions and habitats in local ecosystems which directly affect biological communities in rivers. Mitigation measures can enhance the ecological state of rivers and lakes altered by hydropeaking. They are classified into 3 different types. Operational measures place constraints on the hydropower plants regime itself, fixing threshold values for amount of water released; constructional measures involves construction of hydraulic structures like retention basins; and in-stream measures are renovation or maintenance works carried out inside the river. Mitigation measures are site-specific and thus local investigations must be carried out to ensure successful implementation of measures. In addition, long-term monitoring and systematic evaluation should be conducted during and after the completion of rehabilitation projects to assess the benefits of measures on local ecosystems. The literature review gathers examples of abatement measures implemented in several countries to mitigate negative impacts of hydropeaking. Examples are classified in a table and sorted by the aim of the measures.

PREPARED BY
Julie Charmasson — SIGNATURE

CHECKED BY
Håkon Sundt — SIGNATURE

APPROVED BY
Magnus Korpås — SIGNATURE

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1 Context of hydropeaking and mitigation

1.1 Hydropower production and hydropeaking

The first hydroelectric power plant was installed in Cragside in England in 1870 but the development of hydropower plants to generate electricity at a large scale began in the late 19th century when the electric generator was coupled to the turbine (Kumar et al., 2011). Thus the world's first hydroelectric station (capacity of 12.5 kW) was installed in 1882 on Fox River in Wisconsin, USA, lighting two paper mills and a residence. The installed hydropower capacity increased rapidly in the USA and European countries and these countries had almost reached the current installed capacity by the end of the 1970s. In the last decades, an intensive development of hydropower plants has started in Asia and South and Central America. Today China has the largest installed capacity for hydropower with reaches 200 GW, and it is the largest producer of electricity from hydroelectric plants with a production of 585 TWh in 2008. In a climate change context pushing to increase the share of power production coming from renewable energies, hydropower production would continue to increase in the coming decades. There is still a large potential for this source of energy as the current installed capacity, estimated to 900 GW in 2009 (Kumar et al., 2011), represents barely one fourth of the total worldwide potential capacity estimated of 3700 GW.

Hydropower is considered a clean, flexible, and renewable energy source. However, like many renewable energies, its global benefits can come with significant local impacts and environmental losses. The advantage of hydropower is that water (and thus energy too) can be stored in basins and used at time of peak demand. As a consequence, hydropower facilities are used to track variations in electric needs and follow the hourly consumption, which leads to short-term changes of hydropower plants' operational regimes. **Hydropeaking refers to releases of water retained in storage basins to generate electricity according to variations of the market demand** (Moog, 1993). The frequent water pulses occurring in the river located downstream the hydropower plant may result in severe consequences for local ecosystems. Indeed these artificial flow fluctuations create highly unnatural discharge phenomena in terms of flow magnitude, duration and frequency that would not happen under natural discharge regime. The rapid increases and decreases in water volume often cause large fluctuations in water depth, flow velocity, wetted area and affects also river channel morphology (Moog, 1993), as well as the amount and composition of suspended matter and water temperature. It produces grave impacts on many aquatic organisms such as drift of macroinvertebrates, stranding of fish and changes of their habitat (Parasiewicz et al., 1998). Natural floods supply warning signals (e.g. the rise in ground water level before the flood wave) that would allow organisms to make appropriate behavioral responses (Bretschko and Moog, 1990) while habitat changes which follow unnatural schedules of power generation occur faster than the organisms can adjust to the new conditions. The consequences are often an impoverished aquatic biota (Parasiewicz et al., 1998) which consists of reduced numbers of species, reduced biomass, reduced diversity, and shifts in the composition of communities.

1.2 Characterization of hydropeaking: definition of indicators

1.2.1 Flow regime parameters

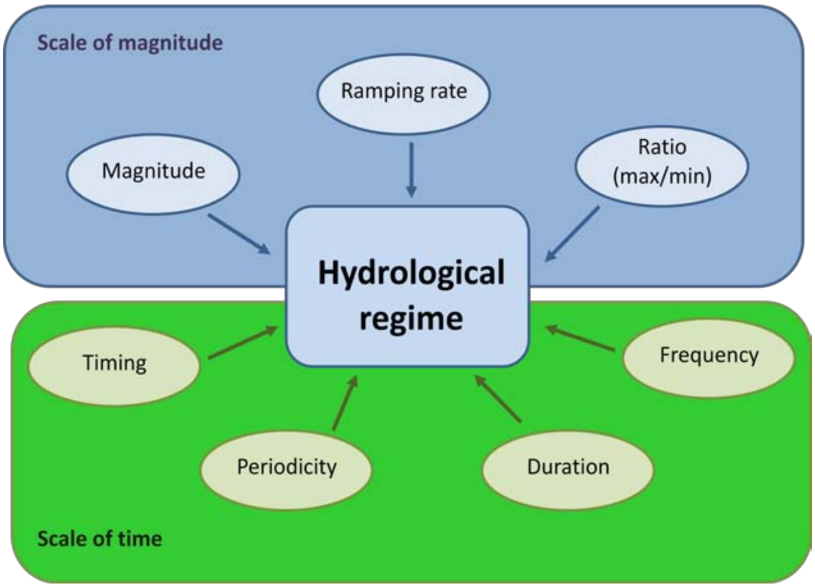

Figure 1. Hydropeaking characteristics impacting hydrological regime of rivers (derived from Schmutz, 2010).

Type of parameter	**Measured parameters**	**Derived hydropeaking indicators**
Magnitude	Maximum discharge Q_{max} Minimum discharge Q_{min} Mean discharge Q_{mean}	Discharge ratio: Q_{max}/Q_{min} Discharge magnitude: $Q_{max} - Q_{min}$ $\Delta Q / Q_{mean}$ Rate of flow increase/decrease dQ/dt Rate of wetted area increase/decrease dA/dt
Time	Duration of the peak Time of start/end of the peak Duration between peaks Duration between low flows stage	Length Timing Periodicity Frequency

Table 1. Parameters and derived values for the characterisation of hydropeaking (derived from Meile et al., 2005)

Hydropeaking consists of variation of discharge and water level occurring during a certain time period. The first step to describe hydropeaking events is therefore to define physical parameters able to quantify the scale of magnitude of peaks on one side, and the scale of time of events on the other side (**Figure 1, Table 1**). The measured discharge hydrograph provides the following key parameters: the discharge value reached at the peak event (maximum discharge), the lowest discharge values before and after the peak event (minimum discharges), and the mean discharge during the studied time period. Then the discharge ratio

(Q_{max}/Q_{min}) and the discharge magnitude **(Q_{max} - Q_{min})** can be calculated for increases and decreases in water volume (Baumann and Klaus, 2003; Meile et al., 2005). Flow fluctuations can be measured either, as described above, by changes in discharge, or by changes in stage. These two units do not have a simple relationship, thus rating tables or rating curves are used to define the flow at each stage for a specific river transect. The calculated rate of flow increase or decrease, expressed generally in m^3/s per minute or per hour (Baumann and Klaus, 2003) reflects the swiftness of change in discharge during a peak event **(dQ/dt).** Both the average and instantaneous rate provides interesting information to assess biological impacts. In addition to these parameters, time series of discharge or water level allow the description of frequency, periodicity, length and timing of hydropeaking events.

1.2.2 River system: biotic and abiotic parameters

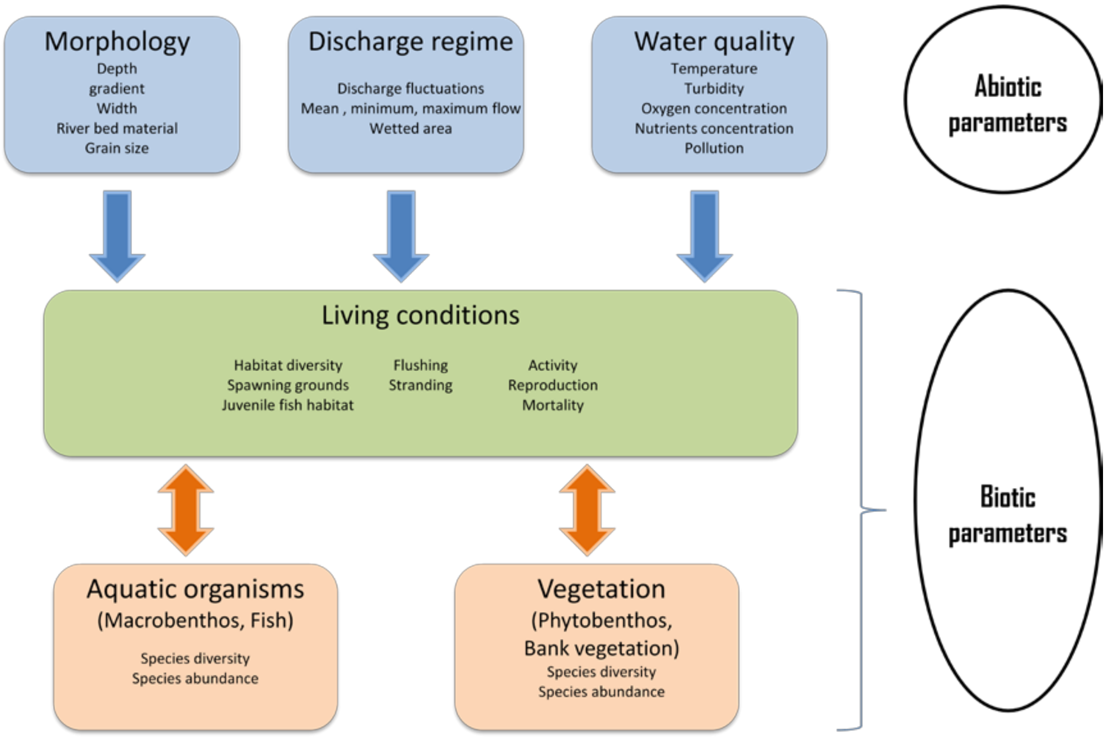

Figure 2. River parameters concerned by hydropeaking (derived from LCH, 2006)

Rivers are complex systems with include interactions between environmental conditions and organisms living in the river or along the shore. Therefore hydrological parameters used to describe peaking events are not sufficient to characterize the hydropeaking phenomenon.

Water level and discharge fluctuations occurring during hydropeaking can lead to variations in water quality (water temperature, turbidity, oxygen and nutrients concentration, pollutants...) and affect the channel and riverbed morphology. The whole of these parameters constitute the abiotic indicators (Bauman and Klaus, 2003).

In addition to the abiotic indicators, the biotic parameters are necessary to describe impacts of flow variations on physical habitat and activity of aquatic organisms, referred as “biotic function indicators", and impacts on composition of aquatic species themselves (vegetation, invertebrates, and fish), referred as "biotic structure indicators". The list of available bio-indicators is as long as the impacts of hydropeaking are varied. Thus a relevant set of parameters should be defined for each study-site (EAWAG, 2005). Baumann and Klaus (2003) reviewed more than 200 studies concerning impacts of hydropeaking. They showed that the most used indicators are:

1. Biotic structure indicators:
   - biomass,
   - frequency/density of species,
   - composition and diversity of species;
2. Biotic function indicators:
   - drifting,
   - stranding,
   - activity/behaviour
   - reproduction.

Sometimes representative species are selected both for their sensibility to hydropeaking events and their capability to represent a whole community of species due to their position in the food chain. Such an example is the stonefly *Brachyptera trifasciata* studied in the Rhine River (Graf and Hutter, 2003).

1.3 Necessity for mitigation

River ecosystems are subject to a large variety of human influences, which goes from water diversion for agriculture, industries or house development to regulation of water flow for energy production (EAWAG, 2005). Recently a public awareness of the need to protect rivers and their ecosystems has emerged within the industrial world (Moog, 1993). Severe degradation of rivers and aquatic ecosystems has been ongoing for many centuries, but the concern for deteriorations in aquatic life directly caused by sudden fluctuations in water volume characterizing hydropeaking has increased since the 1950s only. Consequences for the environment have been described in qualitative terms until the 1990s; but today studies aim at describing damages in quantitative terms and emphasize the environmental stress imposed on communities resulting from a combination of different types of pressures.

Improvement of the status of the environment and counteraction of the decline in environment quality have been supported by various policies and specific rehabilitation schemes, introduced since the 1970s (Feld and al., 2011). In 1972, the United States of America launched the Clean Water Act in order to protect and improve the nation's freshwater resources (U.S. Senate, 1972). Almost 30 years later, the European Parliament passed the Water Framework Directive in order to achieve and maintain a 'good ecological quality' for surface waters in Europe—rivers, lakes, estuaries and coasts (2000/60/EC). Policies with ambitious goals in matter of environment protection define the guideline of impacts studies and implementation of mitigation measures. Then local authorities working together with scientific and hydropower plant companies can launch research projects which aim at remedying the ecological impacts of hydropeaking. Such example is the Rhone-Thur project, focusing on the Rhine and Thur rivers, which aims at establishing scientific foundations for sustainable watercourse management, and involves federal authorities, local "cantons", universities, and environmental and engineering consultancies (Peter, 2006).

Improvements of current degraded state of ecosystems in regulated and hydropeaked water courses can be brought by implementation of abatement measures. Mitigations measures in relation to hydropeaking aim at enhancing the ecological situation of rivers damaged by rapid and repetitive fluctuations of discharge, directly associated with hydropower generation. They are countermeasures based on identified deficits and needs which either help river systems to return to their original condition (restoration) or recreate the key processes and conditions that lead to deterioration of aquatic ecosystems (rehabilitation), (EAWAG, 2005).
Ideally, implementation of hydropower projects in a sustainable manner should be accompanied with the anticipation and pre-project study of all potential environmental and social impacts early in the planning process, so that appropriate steps can be taken to avoid, mitigate, or compensate for impacts (IEA, 2010). Today, the majority of mitigation measures are developed after the completion of hydropower installations. To ensure the success of mitigation projects, EAWAG (2005) suggest a work plan for a rehabilitation project from planning to outcome evaluation (**Figure 3**), which emphasizes the site-specificity of mitigation. In every case, mitigation negotiations for a specific project require development of scientific knowledge of the actual state of the selected river and its ecosystem (Kondolf, 1995). This is generally done by gathering available information since the regulation of the river, such as pre- and post-mitigation hydrological conditions and modifications in the biota which possibly resulted. The second step is to perform in-situ studies, laboratories experiments or/and numerical modeling to specify terms and conditions that minimize the effects of hydropeaking. It can lead to fix threshold values meeting the environmental requirements for running of hydropower plants, or construction of infrastructures to attenuate discharge fluctuations in the river.

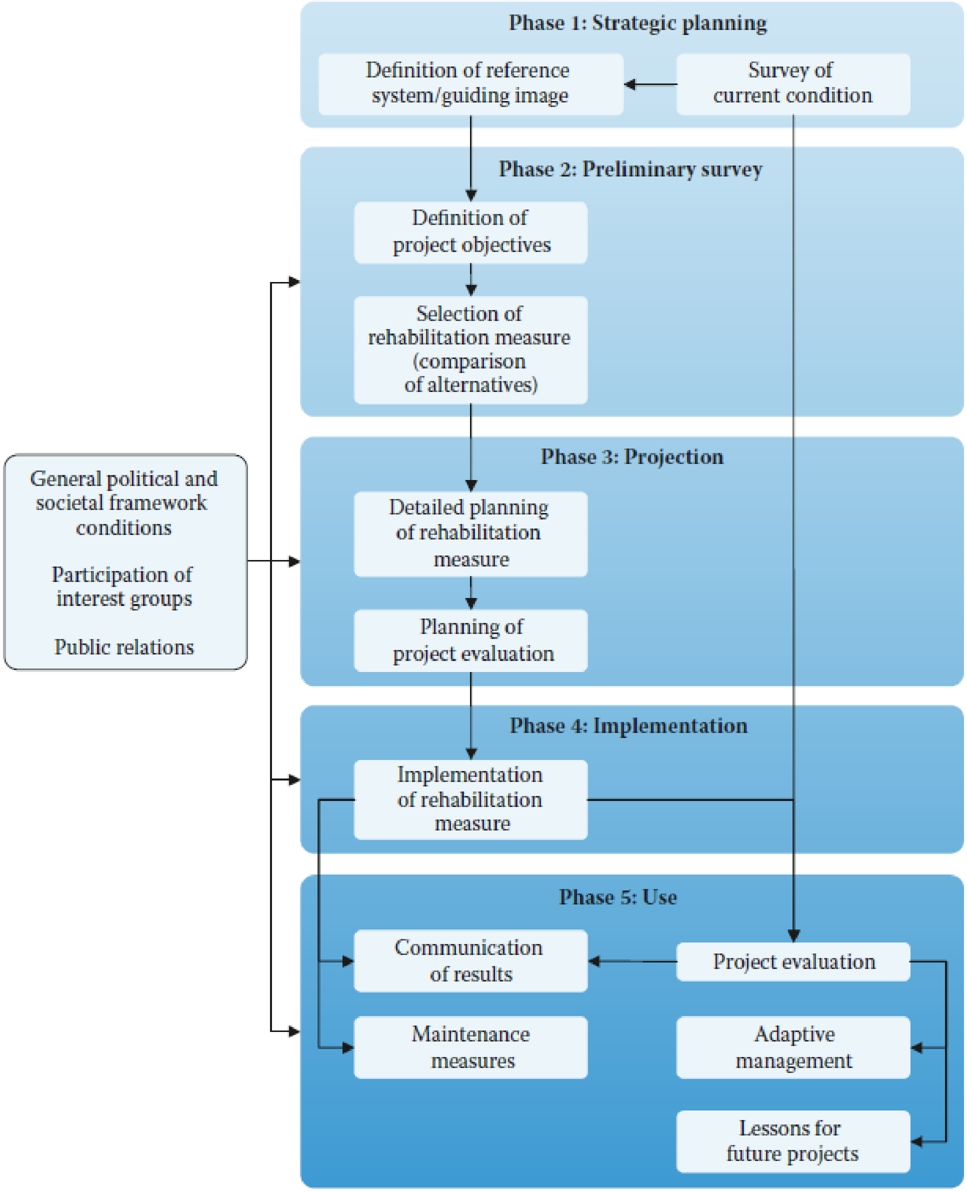

Figure 3. Flow-chart for a rehabilitation project (EAWAG, 2005)

1.4 Requirements for mitigation projects

Complexity of ecosystems and large range of management options to mitigate hydropeaking consequences call for definition of basic objectives applicable to mitigation projects. EAWAG (2005) developed an assessment procedure for Green Hydropower projects which aims at establishing an environmental standard for hydropower plant operations in Switzerland (Truffer et al., 2003). Five ecological domains of the river system are defined as fields to investigate when it comes to mitigate negative hydropower plants consequences in general (Bratrich and Truffer, 2001):

1. Hydrological character
2. Connectivity of river system

3. Sediments and morphology
4. Landscapes and biotopes
5. Biocenoses

Within each environmental field, basic requirements for mitigating negative effects of hydropeaking are described. They are mainly related to the hydraulic regime of the river system (peak frequency, magnitude, swiftness), water quality (temperature, pollution), isolation of fish and fauna out of the main channel, preservation of landscape features and recreational function, preservation of riparian vegetation and flood plains, sustainability of macro-invertebrates and fish communities, the latter regarding stranding, spawning grounds, juvenile fish habitats (Bratrich and Truffer, 2001; Lochner, 2005). **Table 2** gives an overview of the basic mitigation requirements.

Hydropeaking mitigation	
Hydraulic regime	Damping of **flow fluctuations** in regard to frequency, quantity and magnitude of peaks No **dry-out** in the return flow-section
Water quality	No critical effects of **temperature** (ensure releases of ambient temperature water) Ensure sufficient **oxygenation** of water releases
Connectivity of river system	Limitation of **dewatered area** (no isolation of fish and invertebrates outside the main channel)
Landscapes	Preservation of natural **habitat diversity** Preservation of **recreational** function
Flood plains and river banks	Preservation of **flood plains** Ensure **riparian vegetation** growing Ensure physical **stability of river banks**
Macro-invertebrates	**Sustainability of the macro-invertebrates** community
Fish	**Sustainability of the fish** community (conservation of fish habitats, spawning grounds, juvenile habitats)

Table 2. Basic requirements for mitigating hydropeaking effects (derived from Bratrich and Truffer, 2001)

2 Mitigation measures: definition, requirements

2.1 The different types of mitigation measures

Rivers affected by hydropeaking are extremely different from each other. They cover a large range of stream types, from narrow and steep rivers in the Alps, to wide and mild slopes rivers in Canada or USA. Local investigations should be conducted, and potential rehabilitation solutions should always be discussed, to adapt the measures to the river stretch considered, e.g. if it is a reservoir, a fjord, a slow flowing river stretch, a river stretch with rapids or a diverted stretch. The need for abatement will also vary with the season, e.g. in the winter season there is very little recreational use of rivers, and the spring and autumn are the most important periods for fish spawning and fish migration. An optimal solution for defining the requirements of the specific studied river will often be a combination of different mitigation measures. The choice of the measure depends on the type of ecological improvement which is targeted. For example, if the ecological goal is to avoid fish stranding, one measure could be to slow down sufficiently the rise and fall in water level during hydropeaking in order to allow fish to migrate to safe areas. The mitigation measures to attenuate the effects of hydropeaking can be divided into 3 main types:

1) Operational measures,
2) Constructional measures,
3) Compensation and maintenance measures.

1) Operational measures

The first approach places operational constraints on the hydropower plant itself and the maneuvering of the peak. The most common operational measures aim at attenuating the magnitude of peaks (high flow to low flow ratio), slowing down the ramping rate, or limiting and increasing the minimum flow during critical period. Such measures are expected to avoid the direct consequences of peaking operations as pool trapping and stranding of fish (EPIDOR, 2002), drift of macro-invertebrates (Baumann and Klaus, 2003), reduction of fish habitat availability and diversity (Sabaton et al., 2003). For example, studies of the flow regime and local conditions in the in the 23 km-long section of the Alpine Rhin, lying from Domut/Ems to Landquart, allowed the definition of minimum and maximum discharge and range for water level rate of variation for the studied river stretch (Schälchli et al., 2003). Thresholds values (**Table 3**) depend on the target of the measure (e.g. avoid invertebrates drifting, fish stranding). Operational measures engender economic losses because they can constraint the running schedule of power plants by regulating the maximum up and down ramping rates and can also limit their productivity by imposing restrictions on the max/min ratio of operating flow rates or by limiting low flows.

Qmax (m^3/s) Maximum discharge	Qmin (m^3/s) Minimum discharge	Qmax-Qmin (m^3/s) Maximum magnitude	Qmax/Qmin [x : Maximum Ratio	dQ/dt (cm/min) Maximum rate of variation for water level
115 Fine sediments	70	45 Spawning ground	1,6 : 1	
90 Invertebrate drift	45	45 Spawning ground	2;0 : 1	≤ + 0,25 Juvenile stranding
90 Invertebrate drift	35 Fish eggs	55	2,6 : 1	≤ - 0,13 Juvenile stranding
115 Fine sediments	35 Fish eggs	80	3,3 : 1	

Table 3. Threshold values for the Domut/Ems-Landquart section of the Alpine Rhine River for different discharge scenarios. The threshold values (in orange) are defined according the ecological target (in green) and determine the values of other parameters. (Derived from Schälchli et al., 2003).

2) Constructional measures

The second type of mitigation involves the construction of hydraulic structures such as retention ponds (Parasiewicz et al., 1998; LIMNEX, 2001, Meile et al., 2005), artificial reefs in reservoirs, additional channels to deliver water in specific part of the river or in a different lake (Petz-Glechner and Petz, 2002; Baumann and Klaus, 2003, Meile et al., 2005), canals for securing sailing depths, building of multi-level outlet structures in reservoirs (Olden et Naiman, 2009; Sherman et al., 2009), etc. Such structures should smoothen peaking variation by for example storing turbinated waters before continuously discharged into the river. Constructional measures are in general expensive as they imply building of new large structures.

3) Compensation and maintenance measures

The third type of measures are in-stream renovation works to modify characteristics of the river, maintenance measures to protect from erosion for example or compensation programs to compensate for habitat availability lost, e.g. stocking programs of spawning grounds/nursery. A large range of in-stream measures has been settled in rivers to compensate effects of regulation in rivers. They consist in river widening (Hunziger, 2004; Meile et al., 2005; Pellaud, 2006), gravel or sediment placements (EPIDOR, 2002; Pretty et al., 2003, Anderson, 2004; Fette et al., 2011), plantation of trees or grass-faggots (Petz-Glechner and Petz, 2002; Jowett et al., 2009), installations of restoration structures such as weirs, deflectors, cover structures, boulder placements, large woody debris (Baumann and Klaus, 2003; Pretty et al., 2003; Whiteway et al., 2010; Fette et al., 2011).

2.2 Efficiency of measures: the lack of monitoring

Environmental impacts of regulation and hydropeaking has captured public attention and abatement measures have been widely considered as a positive answer to the environmental issue. However some studies have showed that abatement methods can be limited in their capacity to improve the baseline situation (Kondolf, 1995; Roni et al., 2002; Thorstad et al., 2003; Pretty et al., 2003; Stewart et al., 2009). Rivers are complex systems whose geomorphic behavior is not easily predicted. There is a large number of reasons for poor overall response of biomass to the rehabilitation schemes: the schemes turn out to be inappropriate for a specific river, aquatic communities abundance and diversity can lack the potential to increase because of limitation by poor water quality, data can be unreliable, monitoring is conducted during a too short period to allow appreciation of improvements (Pretty et al., 2003; Feld et al., 2011). Besides the long term effects of mitigation measures are only scarcely known. Whiteway et al. (2011) found that, among the 211 reviewed, 86 in-stream restoration projects were monitored for one year after construction, whereas fewer than five projects were monitored for more than 10 years after construction. In addition the characteristics of each site are of major importance. An example of effects of the same mitigation measure in two different cases is shown in **Figure 4** and **Figure 5**. A storage pond was built to attenuate and regulate the outflow from the Linthal and Amsteg hydropower plants (Switzerland). While in Linthal the retention basin had a beneficial effect on peaking and allowed smooth flow variations in the downstream river, the Amsteg retention pond had no visible effect and the flow in the river was following the variation in electricity production. Some measures are also double-edged and are not fully beneficial for the environment. The widening of the river for example can prevent from flood, offer new habitat availability and reduce river bed erosion (Huntzinger, 2004). The new shallow areas offer shelter for young fishes, protected from drifting, but increase the risk of stranding.

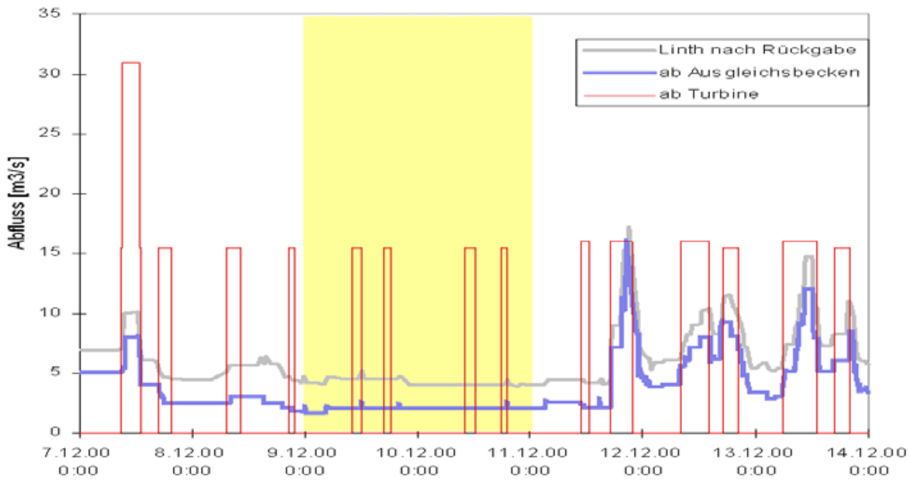

Figure 4. Discharges at the Linthal hydropower plant (HPP). (from LIMNEX, 2001). The yellow band represents the weekend. In grey (*Linth nach Rückgabe*), discharge at the outlet; In blue (*Ab Ausgleichsbecken*), discharge after the retention basin; In red (*Ab Turbine)*, discharge through the turbines.

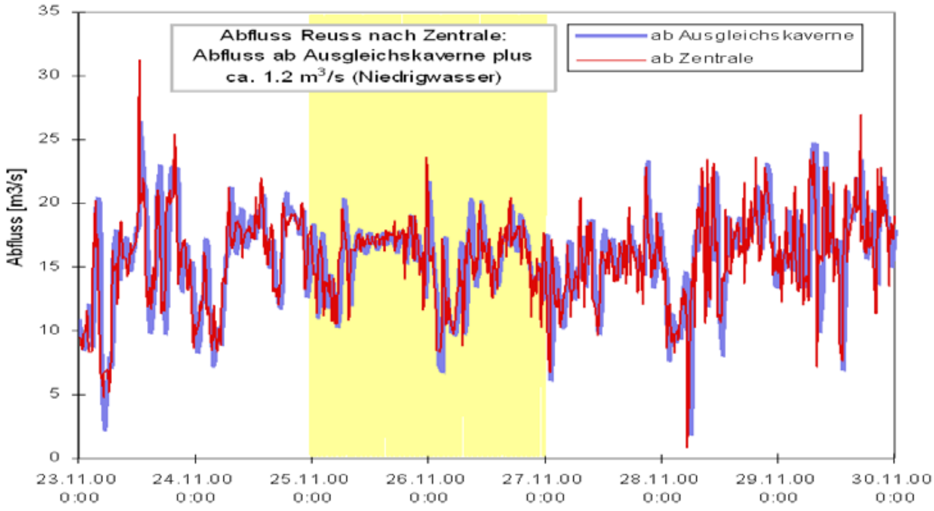

Figure 5. Amsteg hydropower plant. (from LIMNEX, 2001). The yellow band represents the weekend. In blue (*Ab Ausgleichskaverne*), discharge after the retention basin. In red, (*Ab Zentrale*), discharge at the outlet of the hydropower plant).

Few mitigation measures globally have been thoroughly evaluated. Therefore a post-project evaluation is essential to assess the benefits of each measure. In the last decade wide studies, gathering monitoring data from large number of projects, have started to evaluate the effectiveness of stream restoration and in-stream structure measures (Roni et al., 2002; Stewart et al., 2009; Whiteway et al., 2010). However, the scientific literature provides only a few post-mitigation evaluations when it comes to operational and constructional measures. One of the main problems is that the two latter types of measures are mostly set-up after numerical modeling, theoretical calculations or results from laboratory experiments. As a consequence their effectiveness is hardly forecasted. Mitigation measures should be therefore consistently subjected to an evaluation study to determine the beneficial effects.

2.3 Evaluation of mitigation projects

Few evaluation studies of mitigation projects exist and more and more publications now call for a systematic assessment of effectiveness of such projects. An outcome evaluation will allow checking if the objectives of mitigation measures have been achieved or not, based of the comparison of the pre-project and post-project states. Kondolf (1995) suggest that systematic post-project studies include five elements:

1. Clear objectives must be defined qualitatively and quantitatively when it is possible, and will constitute the base for the evaluation;
2. Baseline data must be collected and should start before the project construction. Reference values should come from pre-project measurements, existing reference systems, historical references, or alternatively theoretically reference system built from scientific knowledge;
3. Evaluation approach must be coherent and based on the systematic comparison of parameters over years;
4. Long term monitoring needed to be conducted in order to assess changes that require years to manifest (cf. section 3.2):

5. Willingness to acknowledge failures is fundamental.

Results from restoration projects provide highly valuable inputs for future projects. Kondolf's method refers to river and stream restoration projects, which are mainly focusing on in-stream work, but could be applied in different mitigation projects. Within the Rhone-Thur project (http://www.rhone-thur.eawag.ch), EAWAG designed a tool to evaluate the effectiveness of rehabilitation projects. The evaluation is based on definition and use of indicators (practical parameters) that can be measured and interpreted (Weber et al., 2006). The tool describes 50 indicators, divided in 18 groups (Woolsey et al., 2005):

- Project acceptance, Stakeholder participation,
- Costs,
- Landscape,
- Longitudinal connectivity,
- Transition zones,
- River bank,
- Vegetation,
- Bedload,
- River bed,
- Organic materials Hydro-geomorphology and hydraulics,
- Temperature,
- Macro-invertebrates,
- Fish,
- Fish habitat,
- Refugia,
- Recreational use.

A set of indicators, should be defined for every rehabilitation project, including the indicators which characterize specific objectives of the rehabilitation project (Weber et al., 2006).The list established within the Rhone-Thur project provides input parameters to be evaluated in future rehabilitation projects as well as in mitigation measures. New indicators should of course be designed in the specific field of mitigation of hydropeaking impacts, based on the parameters defined in section **2.2**. Once the appropriate indicators of a mitigation project have been chosen, a systematic and rigorous method can be applied to evaluate the improvement of ecological state of rivers after completion of measures. The evaluation method described by Woolsey et al. (2005) consists in the comparison of the indicators values prior to and after completion of projects. Indicator values which are calculated in their own unit are converted into dimensionless numbers, scaling form 0 to 1, and reflecting the “degree of naturalness”. Afterwards, with the help of an assessment matrix (**Figure 6**), the comparison of the pre- and post-projects' standardized values determine the category of change for each indicator (**Figure 7**). Considering the degree and type of change, and the initial state, the outcome will be assigned to one “success category”, ranging from “deterioration” to “great improvement”.

Value after rehabilitation \ Value before rehabilitation	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0.0	0	–	–	–	–	–	–	–	–	–	–
0.1	+	0	–	–	–	–	–	–	–	–	–
0.2	+	+	0	–	–	–	–	–	–	–	–
0.3	+	+	+	0	–	–	–	–	–	–	–
0.4	+	+	+	+	0	–	–	–	–	–	–
0.5	++	++	+	+	+	0	–	–	–	–	–
0.6	++	++	++	+	+	+	0	–	–	–	–
0.7	++	++	++	++	++	+	+	0	–	–	–
0.8	+++	+++	++	++	++	++	+	+	0	–	–
0.9	+++	+++	+++	+++	+++	++	++	++	++	0	–
1.0	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	0

Figure 6. Matrix for comparing standardized indicator values (before and after measure was implemented) (Woolsey et al., 2005)

Symbol	Change	Explanation
–	Deterioration, failure	The difference between the condition after the measure and the initial situation is negative.
0	No change	The difference between the condition after the measure and the initial situation is 0.
+	Small improvement, small success	The difference between the condition after the measure and the initial situation is positive. Classification depends on the initial situation.
++	Medium improvement, medium success	The difference between the condition after the measure and the initial situation is positive. Classification depends on the initial situation.
+++	Great improvement, great success	The difference between the condition after the measure and the initial situation is positive. Classification depends on the initial situation.

Figure 7. Categories of change. (Woolsey et al.,2005)

2.4 Economical costs of mitigation measures

The advantage of hydropower plants is that they work as batteries as they are able to deliver electricity depending on the market demand. Restrictions for minimum/maximum discharge and for ramping rate have therefore a strong impact on productivity because it reduces flexibility. Calculations of economic losses due to operational adjustments to match the ecological requirements are almost absent from scientific literature, but some calculations can be found in technical reports from power plant operators. E.D.F. (Electrité de France) calculated the costs to keep a minimum discharge of 20 to 65 m³/s in the Dordogne River(EPIDOR, 2002). Estimated costs ranged from 335 to 3110 k€ per year and increased with the level of minimum flow. Another 760 k€ were needed to cover expenses for technical adjustment of the turbines.

Constructional measures have a restricted impact on the hydropower plant running as they consist in structures located mainly at the outlet of the power plant. Thus the productivity is generally not affected, but the costs for building retention reservoirs, tunnels or installing of equipment can be relatively high. In Switzerland, the costs of an attenuation reservoir of 100 000 m³ to mitigate peaking in Ticino River are estimated at 4 Mio€ (LCH, 2006). The costs associated with retrofitting a dam with a multi-level outlet structure are typically quite high. Costs increase dramatically for deeper dams/reservoirs. The actual costs for Shasta Dam (USA) were $80 Mio (55 Mio€) for a volume of 5 400 000 m³ (Sherman, 2001). The estimated costs for retrofitting several reservoirs in Australia range from 3 to 17 Mio€ for volumes between 36 000 and 1600 000 m³. Schleiss (2009) points out that even if the investment to set-up constructional measures are relatively high, these measures are more acceptable from an economic point of view than operational measures which lead to economic losses every year and as long as the power plant is running.

In-stream renovation works have much lower costs than operational and constructional mitigation measures, but they have a shorter life span as they are designed to last about 20 years (Frissell and Nawa, 1992). Purchase and placement of 120 t of gravel in Campbell River in Canada cost 17 000 € (Anderson, 2004). Whiteway et al. (2011) reported that the median cost of the in-stream restoration projects in their analysis were 25 000 €. In the Dorodgne River, building of shelters for fish and invertebrates by deposition of rocks was estimated to 12500€ for a 200 m-long river stretch. Thus the lower costs induced by in-stream renovation measures are mainly due to the restricted area targeted by the mitigation measures. In general, in-stream works act on geographically restricted area and aim at improving habitat conditions in specific sites of the watercourse. On the contrary, operational and constructional measures apply in large sections of rivers, e.g. the whole river stretch located downstream a power plant.

3 Examples of mitigation measures

3.1 Austria: Mitigation in Bregenz River

3.1.1 Pre-mitigation study

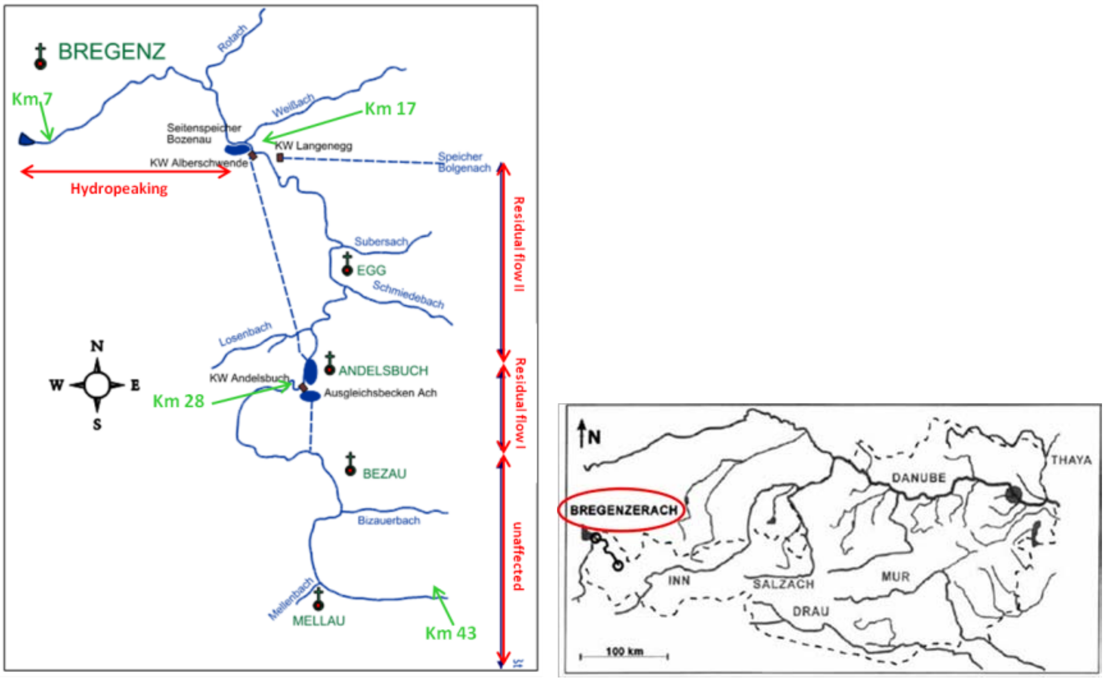

Figure 8. Map of the study site (left) and location of the Bregenz Riverin Austria (right) . In green, distance in kilometers from the downstream boundary. From Schinegger R. et al, (2009).

Prior to mitigation, two hydropower plants regulated the flow in the studied section: Andelsbuch, the uppermost, located at river kilometer 28 (counting starts at the downstream boundary); and Langenegg, the lowermost, located at km 17. For discharges below 30 m³/s in the Bregrenz River the uppermost hydropower plant used the entire flow. The lowermost plant used the flow from a tributary (Bolgen River), and added another 30 m³/s to the total discharge in the Bregrenz River. In the river section located between Langenegg power plant and Lake Constance, which is also referred as the hydropeaked stretch, the total peak discharge could thus reach 60 m³/s, giving a peak magnitude ratio Q_{max}/Q_{min} of 60:1.

Before mitigation measures, fish and invertebrates fauna were heavily affected by hydropeaking. **Figure 9** shows the fish biomass in three different sections of the studied river stretch. The results show that the biomass was highest in the unaffected section, upstream the power plants, and reached about 45 kg/ha. The biomass was slightly inferior in the section with residual flow, located between both power plants, but it was dramatically low in the hydropeaked section, located downstream Langenegg plant, with about 3 kg/ha. The same pattern was found for the benthic biomass. In the reference sites (located in the uppermost section), the benthic fauna was much higher than in the hydropeaked section (**Figure 10**) where the biomass was 15% of the expected values predicted by an altitude model (Parasiewicz et al., 1998).

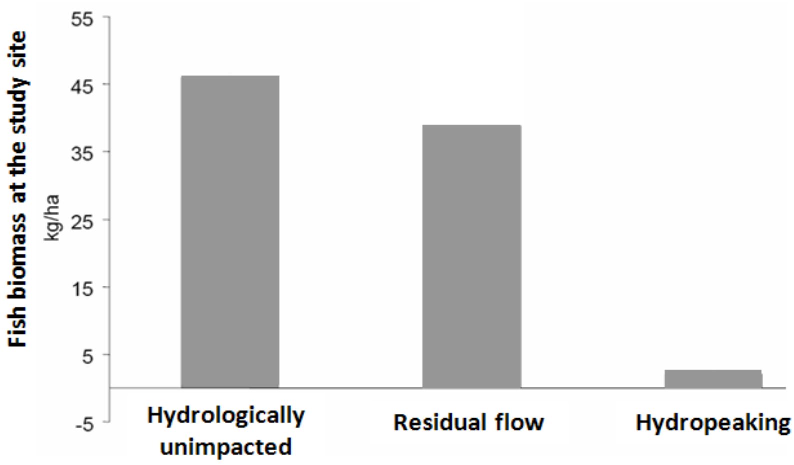

Figure 9. Fish biomass in the different sections of the study site before mitigation (Schinegger R. et al, 2009).

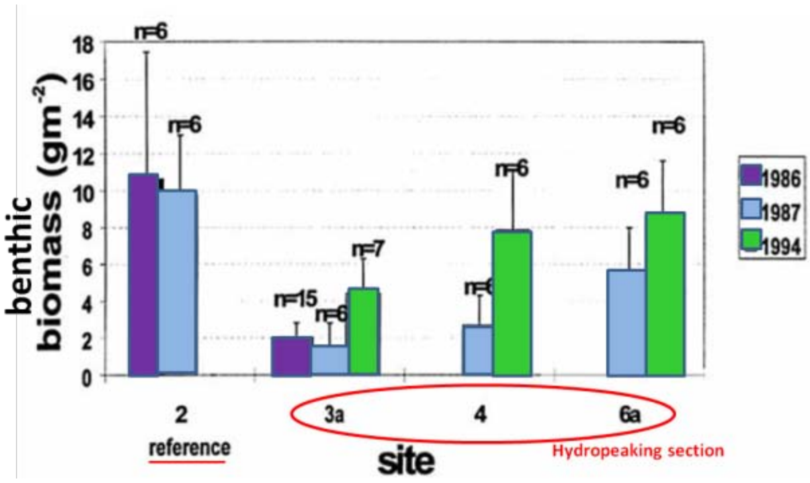

Figure 10. Benthic biomass in the different sections of the study site before and after mitigation (from Parasiewicz et al., 1998)

3.1.2 Mitigation measures and monitoring

In 1992, mitigation measures were implemented in parallel to the construction of a new hydropower plant. A regulation reservoir was built below Andelsbuch power plant. The water released from the reservoir was flowing through a new hydropower plant, of type “run-of-river” which was constructed beside Langenegg power plant. Below both the run-of-river power plant and Langenegg power plant, a second re-regulating reservoir was built. In addition to the constructional mitigation measures, a flow management regulation was implemented to reduce the peak amplitude. It consisted in installing a 24h pre-peaking period before expected peaks.

During the pre-peaking phase, base flows were increased in proportion to the planned peak discharge, with a magnitude set to fill the river bed.
Mitigation measures led to changes in hydrological regime of the river. Prior to mitigation, the magnitude ratio Q_{max}/Q_{min} was 60:3, and no pre-peaking period occurred in the river. After mitigation, the magnitude ratio was modified to 60:20:3. Since the planned surge releases were quite frequent, the base flow remained relatively stable (it was increased during every pre-peaking periods); and in average the base flow was higher than before mitigation. Ramping rates of peak were severely decreased after mitigation: by 75 % for the ramping rate of the bed-filling peak, and by 25% for the main peak.
These changes were favorable to benthic invertebrates' survival, whose biomass increased from 15 to 60 % of expected values in the hydropeaking section, after mitigation (**Figure 10**). No significant increase of the fish fauna was observed. Nevertheless some larger fish were caught in the stretch, probably due to availability of larger flow-refuge areas.

3.2 France: Mitigation in the Dordogne River and its tributaries

3.2.1 Pre-mitigation study

The Dordogne basin is provided with 4 hydroelectrical chains, located along the Dordogne River and its affluents (Maronne, Cère, Vézère). 52 dams and 28 hydropower plants give a total capacity of 1800 MW, and a production of 3000 GWh. The hydroelectrical complex has a storage capacity of 1.1 billion m³ of water.

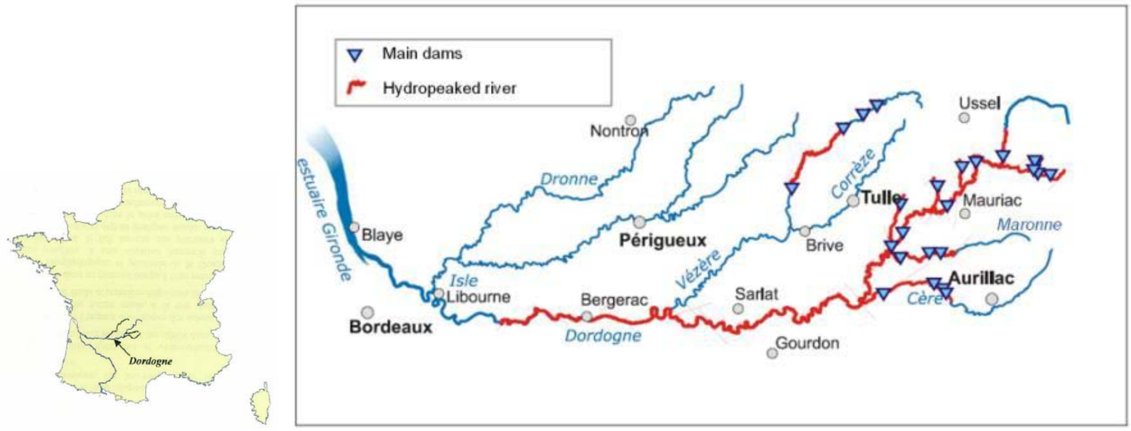

Figure 11. The Dordogne basin (Guerri, 2005)

The main hydrological changes caused by the regulation of the Dordogne and its tributaries are faster flow variations, higher frequency of flow variations, higher frequency of low flows in winter and spring, higher frequency of high flows (Guerri, 2005). Several kinds of environmental impacts have been identified:

- Direct impacts on fauna (dewatering of spawning grounds, pool trapping and interstitial stranding, fry and invertebrates drift.)
- Global impacts on ecosystems (morphology of the watercourses, vegetation, bed load)

- Impacts on the recreational use (fishing, highly depending on flows values; swimming (drying out of beaches for high flows, difficult access to beaches for low flows); kayaking (danger above a certain value).

Figure 12. Drying out of the Pinsac branch of the Dordogne River (Cazeneuve et al., 2009).

After 15 years of observations and studies in different sites of the Dordogne Basin, an agreement between EDF (which has the concession to run all the power plants located in that catchment), some local public agencies and the French State been signed in 2009. It defines the minimum requirements that have to be satisfied in order to mitigate the impact of the regulation of the Dordogne and its affluents. The mitigation measures refer to:

- Flow and rate of in/decrease values to respect
- River planning and constructional works to start

The flow values depend on the season, according the biological cycle of the species living in the studied rivers. All regulations and river planning have been defined for specific geographical areas. **Table 4** sums-up all regulations and recommendations in each site along the year. Two examples of mitigating measure already realized are detailed below.

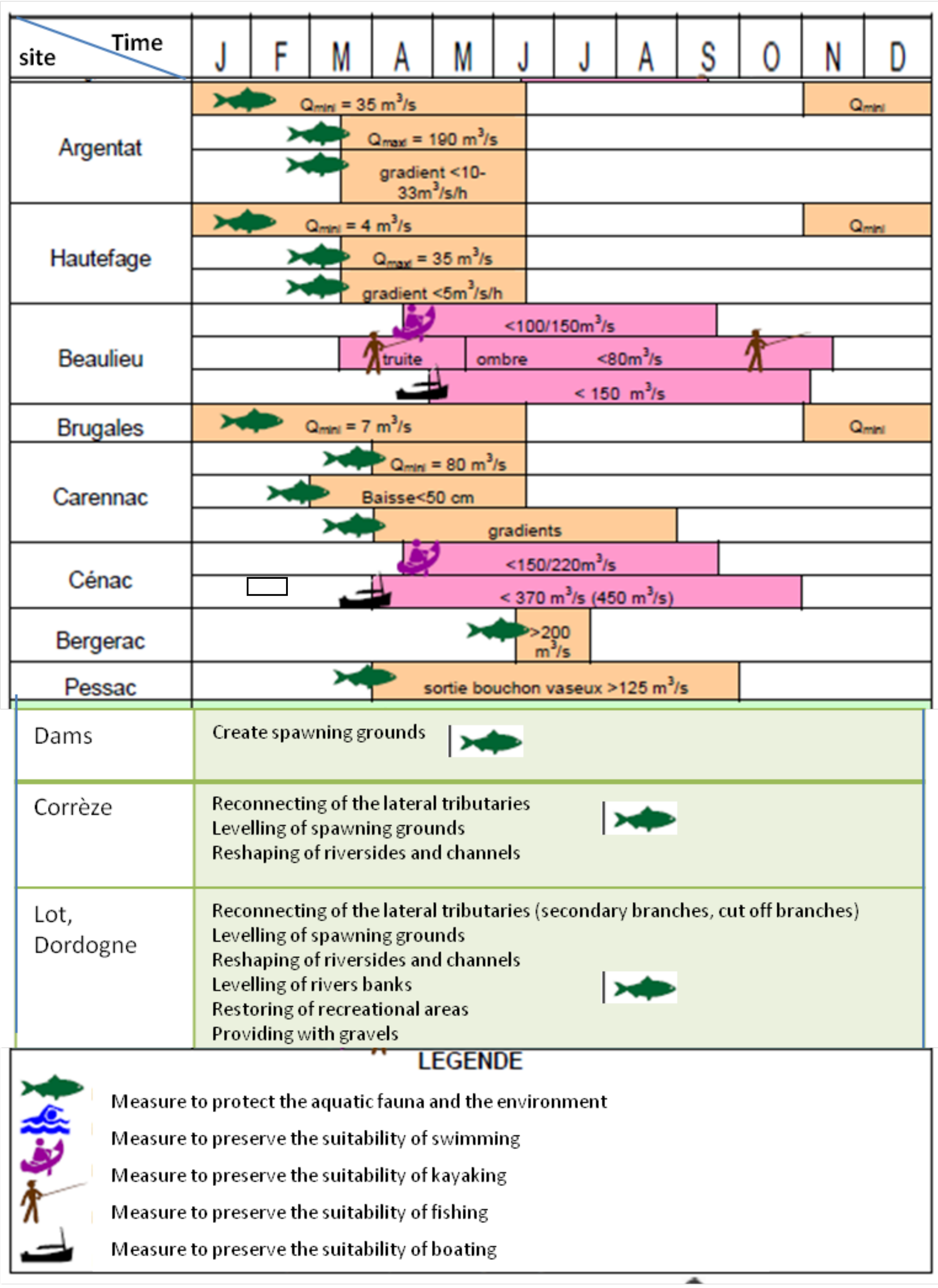

Table 4. Synthesis of the flows regulations ([orange] flows regulations; [pink] flows values recommended for some activities) along the year and works ([green]) in the studied sites (From EPIDOR, 2009).

3.2.2 Mitigation measures and monitoring

Dewatering of spawning grounds

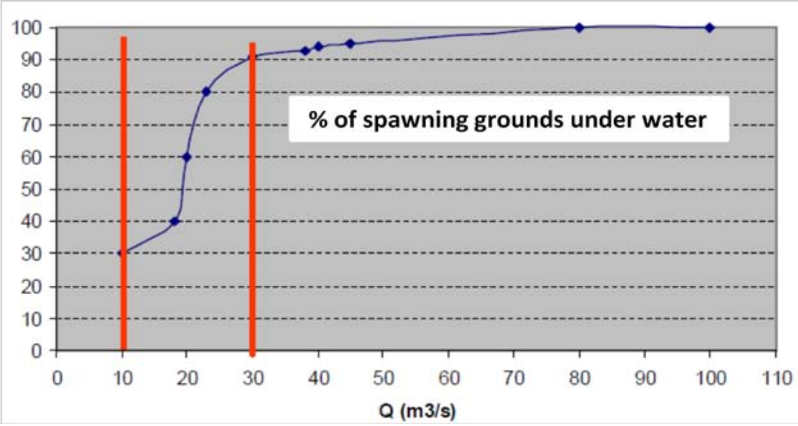

Figure 13. Calculated % of salmonids under water according flow values. (Cazeneuve et al., 2009)

In the Dordogne River it has been observed that salmonids spawn close to the river banks (in average at less than 5 m from the bank), where the size of bed load and the speed of the current match with the spawning phase (Cazeneuve et al., 2009). Therefore, due to their location, these spawning grounds are highly affected by flow variations. The first solution was to maintain a higher minimum flow downstream the Sablier Dam (where half of the studied spawning grounds have been located). The hydraulic model and the observations led to the conclusion that for a minimum flow of 30 m^3/s, 90% of the spawning grounds would stay under water (**Figure 13**). Therefore an increase of the minimum flow from 10 m^3/s to 30 m^3/s has been required downstream the Sablier Dam during the specific period from 15 November to 15 May. A discharge of 80 m^3/s would prevent any dewatering of spawning grounds which was hardly possible in that period. Therefore, in addition to the increase of the minimum flow, another measure was taken in specific sites of the river where most of the spawning grounds were still dewatered at the new minimum flow of 30 m^3/s. In the "Lycée d'Argentat" site, the area with appropriate size of bed substrate for spawning has been leveled to ensure that all spawning grounds remain under water at the minimum flow (**Figure 14**). Monitoring of the mitigation measures shows that leveling at the Argentat site was successful and beneficial for fish. During the 4 years following the works, no spawning grounds were dewatered while the population was even higher in 2006 and 2007 (**Figure 15**).

Figure 14. The "Lycée d'Argentat" spawning site for a flow of 32 m^3/s, before the works (left) and after (right). (Cazeneuve et al., 2009).

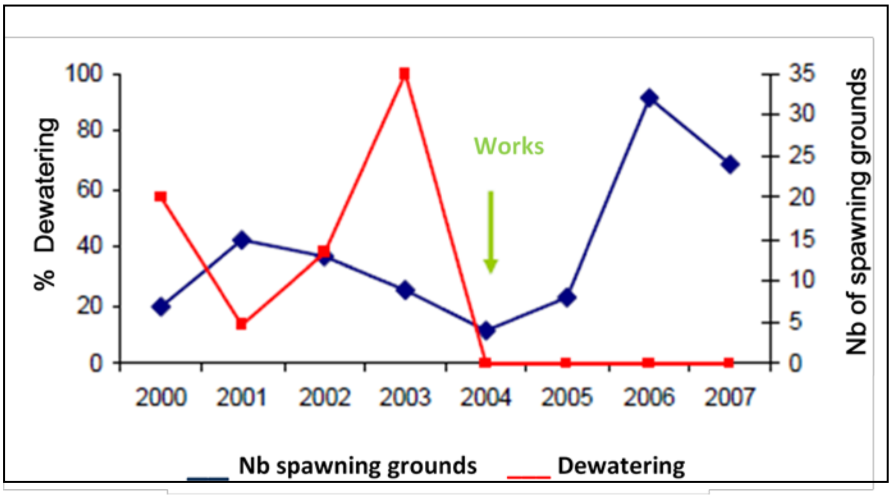

Figure 15. Number of dewatered spawning grounds at the "Lycée d'Argentat" site. (Cazeneuve et al., 2009).

Pool trapping of juvenile fish

In-stream observations of alevins' mortality between 2005 and 2007 showed that pool trapping of salmonids' alevins increase with the tailwater's flow during the swim-up period (when alevins leave their yolk sacs). The alevins' mortality doubled when the flow is over 240 m³/s downstream the confluence of the Maronne and the Dordogne Rivers (**Figure 16**). Therefore one solution was to have a maximum flow required of 240 m³/s at the confluence during the swim-up period (mid-March until mid-June, in that case) to avoid pool trapping. In spite of the regulation of the maximum flow, juvenile fish was still affected in some specific sites. An additional mitigation measures was to modify some sites where high mortality has been regularly observed, even at flows lower than the maximum flow required. Works modified the site morphology to ensure the elimination of the pools and avoid trapping. Leveling of the Chambon site (**Figure 17**), located downstream the Argentat's dam, led to a strong decrease of mortality from about 300 salmonids' alevins to less than 50 for the same maximum flow reached during hydropeaking which is about 140 m³/s in this location (**Figure 18**).

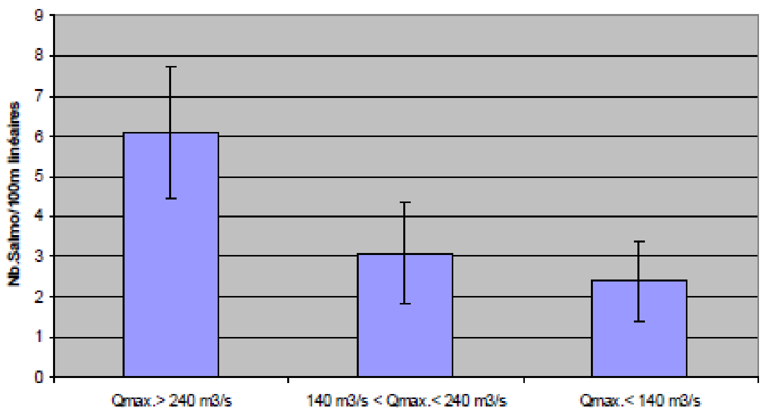

Figure 16. Relation of number of alevins pool-trapped in 8 different channels downstream the confluence to the maximum flow during hydropeaking (average number and standard deviation). (Cazeneuve et al., 2009).

Figure 17. “Chambon” site before (left) and after (right) works. (Cazeneuve et al., 2009).

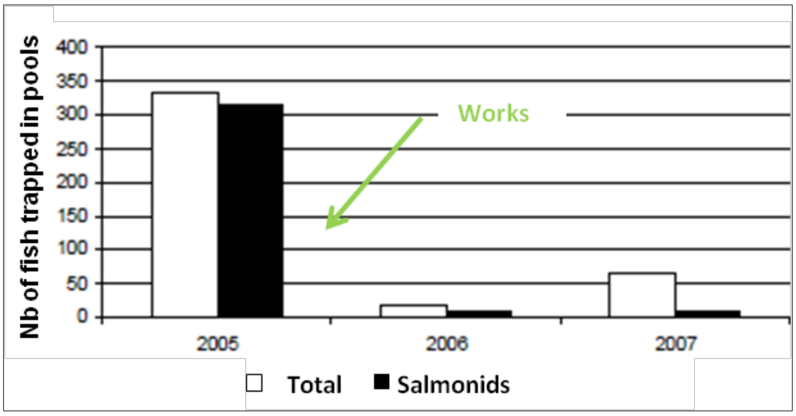

Figure 18. Evolution of the number of young fish trapped in pools at the Chambon site. (Cazeneuve et al., 2009).

4 Hydropeaking mitigation measures in Norway

4.1 Overview: Hydro power development in Norway and research about mitigation measures

In Norway, hydro power was used for mills and later for textile and mechanical industries, before the first electricity plants came at the end of the 19th century. In the period 1900-1940, more than 2000 power plants were built, typically located close to the consumers. During this time, the high gradients in the lowest parts of the rivers were used, and most power plants were run-of-the-river installations. To use also water from lakes, pipes were built to convey it down to the power plants. After World War II, the rebuilding of the country led to increased demand for electrical power, and many new plants were constructed. This continued until the 1970- and 1980-ies. It became more and more common to establish large water reservoirs in the mountains. These "many-year-reservoirs" were created to guarantee enough electricity production also during cold years or periods with low precipitation. The water is collected and stored in the mountains, before it runs through tunnel systems down to the power plants. These are often situated inside the mountain, having their outlet into a lake or fjord. Large-scale hydro power development in Norway practically stopped in the 1990-ies, when the most profitable sites were developed, and a new energy law allowed for competition in the sector. Since that, only small hydro power plants have been built (Hveding 1992, OED 2011).

Today, hydropower produces 99% of the electricity in Norway, and a large number of rivers are regulated. The Norwegian Water and Energy Directorate (NVE) has overall responsibility for maintaining national power supplies, including energy regulation and licensing. NVE's mandate is also to ensure an integrated and environmentally sound management of the country's water resources, administrating Norway's hydrological data base and being involved in research and development in these fields. Thus, NVE has been protagonist and coordinator for many research projects dealing with the environmental effects of hydro power and mitigation measures.

The traditional regulation scheme for hydropower was characterized by storage of water in the summer, to use it for energy production in winter. Typical consequences were the absence of large floods, reduced flood discharges, lower discharge during the summer and increased discharge in winter. Observed effects in the by-pass section were reduced spawning- and living areas for fish, increased sedimentation and vegetation growth, and increased influence of groundwater. Below the outlet of the power plants, changes of water temperature and substrate were observed (Saltveit 2006). In 1993, a state-of-the-art publication concerning watercourse exploitation by emphasizing the effects of hydropower regulation summed up the results of two research programs "Biotope Adjustment Program" and "Post-Regulation Studies" (Faugli et al. 1993). During this time, the phenomenon of hydropeaking was recognized for example for the temperature behavior of a few power plants (Figure 19), but it was not a widely known problem yet.

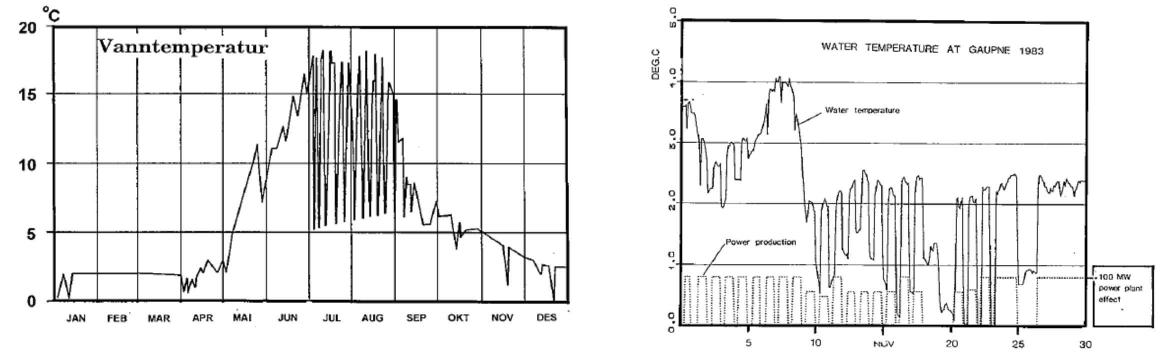

Figure 19. Hydropeaking influenced temperature curves in the Flatdalselva near Selfjord downstream of the Sundsbarm power plant outlet in 1976 (left) and in the Jostedøla river downstream of the Leirdøla power plant outlet in November 1983 (right). From Faugli et al. (1993).

In 1990, a new energy law was introduced and the energy marked was deregulated. Differences in prices between day and night, and an increase in the import and export of electrical energy led to changes in power production patterns to achieve maximum economic benefit. At many hydro power plants this caused fast fluctuations of water level and discharge in regulated rivers or reservoirs. In the period 1996-2000, NVE coordinated a research program "Diurnal hydropeaking – environmental effects and conflict-reducing measures" that was focused on the effects of hydropeaking on erosion and sedimentation in reservoirs, ice and water temperature, erosion protection, local climate, biology and optimalization with respect to techniques, environment and economy. The results showed that diurnal hydropeaking could increase erosion problems in rivers and reservoirs and affect fish, invertebrates and vegetation negatively, especially because of fish stranding. The stranding problem and other consequences of hydropeaking for ecosystems in flowing water were investigated within research projects of the Norwegian Institute for Nature Research (NINA), the Norwegian Institute for Water Research (NIVA), NTNU, SINTEF and the Laboratory for Freshwater Biology and Inland fisheries (LFI).

Another research program "Environmental based flow" has aimed to contribute to the assessment of hydropower regulation effects and to find good mitigation measures. The program has been realized through a close cooperation between research institutions, the Directorate for Nature Administration and the energy sector. The first phase of the project was carried out 2002-2006 and concentrated on the following aspects: low discharge, ground water, water temperature, sedimentation and erosion, biology, aesthetics, and other mitigation measures (Brittain 2007). The results were compiled into a new state-of-the-art publication which included the EU Water Framework Directive (WFD) as base for the work of the water administration (Saltveit 2006).

The second phase of the project has lasted from 2007-2011 (Sivertsen 2009). This phase has been focused on analysis and assessment of:

- Effects, costs and public acceptance of realized mitigation measures such as groins, fish passages, minimum discharge and biotope improvements
- Effects of small hydro power plants on landscape, flora and fauna
- Effects of hydro power regulation for endangered species and biological diversity
- Environmental effects of hydropeaking
- Models and methods for planning of mitigation measures.

The Norwegian activities for river restoration are not only related to hydro-power mitigation, because many rivers have been channelized for lumber transport or agricultural purposes, or have been affected by flood or erosion protection measures. After the adoption of the WFD in 2000, a program for environmental measures in rivers that had been subjected to regulation or other engineering measures was initiated (Hamarsland et al. 2003). The program exemplified possible measures in more than 90 rivers that could be performed within 10 years, depending on the state budget and local initiatives.

4.2 Hydropeaking mitigation measures in Norway

4.2.1 Operational measures

Operational measures for rivers

Minimum flows have been introduced more than 20 years ago and deserved much attention in the research programs (Faugli et al. 1993, Brittain and L'Abee-Lund 2001, Brittain 2007). A central parameter for the treatment of concessions in Norway has been the "Common Low Water" ("allminnelige lavvannføring"), a minimum discharge that equals approximately 5-15 % of the mean annual discharge and which is highly correlated to the mean annual minimum value of the daily discharge (Skaugen et al. 2001). More recently, the applicability of methods from other countries for Norwegian conditions has been investigated, with the recommendation to use simplified statistical habitat models and analyses of ecologically relevant parameters for small and medium projects and holistic methods for large ones (Halleraker and Harby 2006). A proper defined minimum flow was shown to provide good habitat conditions for fish, such as Atlantic salmon (Johnsen and Hvidsten 2006).

In practice, static minimum flow regimes are mostly used, having fixed values for winter and summer flow. Nowadays, alternative solutions of environmental flow regimes that are designed to follow the variation in natural inflow or special habitat requirements have been developed (Gravem et al. 2006, Halleraker et al. 2007, Alfredsen et al. 2011). Also landscape-esthetical aspects have become more important, especially with respect to waterfalls that need site-specific minimum discharges to keep alive their visual impression (Simensen et al. 2011).

Reductions of the ramping rate for the power plant outlet into rivers have been recommended based on stranding experiments and biotope model simulations (Saltveit et al 2001, Borsanyi et al. 2001, Halleraker et al. 2003, Johnsen et al. 2010). The stranding risk is reduced during nighttime and at specified temperatures, see. Chapter 4.3. Arnekleiv et al. (2007) have shown that fish migration can be supported by the choice of the proper release type (deep water or surface water) at river dams.

In rivers where enhanced growth of aquatic macrophytes has become a problem, a temporal halt of the power plant during cold can be taken into consideration, to expose submerged macrophytes to frost. Flushing flows to scour sediments and the associated macrophytes could be another operational measure to deal with this problem (Rørslett and Johansen 1996).

Operational measures for reservoirs

In reservoirs with glacio-fluvial, glacio-lacustrine or recent fluvial deposits on their banks, it may be necessary to adjust the regulation limits and to reduce the maxiumum rate of variation for lake stage to control hydropeaking induced groundwater erosion, as illustrated in Fig. 20 for Vinjevatn reservoir. For this and other lakes, simulations or hydropeaking test runs and sediment measurements were performed to study erosion processes (Løvoll et al. 1999, Bogen and Bønsnes 2001, Bogen et al. 2002). Biological studies showed that the draw-downs in reservoirs should be slow also to prevent stranding of benthic invertebrates and juvenile fish, and short-term regulation between heights that reveals large areas of dry land should be avoided (Brodtkorb 2001). Reducing the designed fluctuation range is a recommended measure to restore native aquatic vegetation in and reservoirs that are devoid of macrophytes (Rørslett and Johansen 1996).

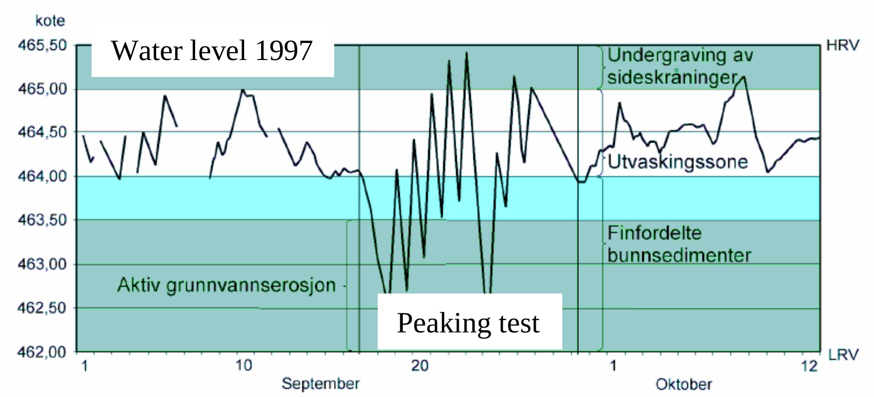

Figure 20. Diagram illustrating the erosion processes at different lake stages for Vinjevatn (Telemark, Southern Norway). In the out-washing-zone (utvaskingssone), fine-distributed sediments are washed out. Ground water erosion (grunnvannserosjon) is most relevant below level 463.5, but may play a role also at other levels. From Bogen and Bønsnes (2001).

4.2.2 Constructional measures related to the power plant

Many power plants practicing hydropeaking have their outlets into large freshwater lakes or fjords, where the negative effects on temperature or water level are negligible (Saltveit 2006). For power plants with outlet into a river, retention ponds might be an alternative to prevent negative effects of hydropeaking also in Norway (Løvoll 1998).

The effects of temperature differences because of hydropeaking can be damped by using intakes situated in different heights of the reservoir, as for example in Alta power plant (Pytte Ascall 2005, Johnsen et al. 2011).

Hydroelectric dams provide different fish migrating pathways such as turbines, sluiceways and fishways with varying efficiency, depending on physical properties of the technical installations (e. g. Linløkken 1993, Thorstad et al. 2003). Arnekleiv et al. (2007) investigated the use of downstream migration possibilities by iteroparous salmonid species at a dam during the autumn and spring descent and formulated threshold values for descending kelts.

Norway has a long tradition of building fish passes. The first of them were built early in the 1870-ies with the goal to increase the river length accessible for Atlantic salmon, i.e. not necessarily in connection with hydro power installations. Today, more than 500 fish passes exist, most of them designed for Atlantic salmon and sea trout. They are regarded as an important measure to protect endangered fish species and to re-establish fish communities where they have disappeared. It is planned to restore many of the old fish passes within the next years (DN 2002, DN 2011).

4.2.3 Measures in the water body

In-stream measures

In-stream measures to mitigate hydropeaking effects are often combined or identical with measures to improve the ecological status of rivers in general, or to improve the habitat conditions and survival for fish. Hamarsland et al. (2003) suggested for this purpose measures such as re-meandering of channelized reaches, re-opening of side-channels, digging of pools, construction of groundsills or groins, dumping of stones or spawning substrate, establishment of bank vegetation, removal of fish barriers, modification of old erosion-protection constructions and re-opening of piped streams. The measures described below are supposed to be especially useful for hydropeaking mitigation.

Groundsills or weirs ("terskler") have often been built in rivers affected by the regulation to increase the water level and improve fish habitat (Fig. 21). Much knowledge about their construction and effects for fish, invertebrates and vegetation is available from a research project (Weir Project, 1973-83) and more than 400 practical applications (Faugli et al. 1993, Sæterbø et al. 1998, Johnsen et al. 2010). A monitoring and evaluation project showed that these measures were mostly successful, but that future applications should prefer constructions of lower height in combination with river bed adjustments (Arnekleiv et al. 2006). Weirs can have a positive effect also for the temperature (Saltveit 2006).

Groins, stone settings, river bed adjustments and digging of pools are other in-stream measures that have been successfully used. Stone settings and pavements help to sustain a sufficient number of rapids between weirs or pools to improve the conditions for fish migration and to create habitats for rheophilic fish and invertebrate species (Sæterbo et al. 1998, Arnekleiv et al. 2006, Johnsen et al. 2010). The survival of young fish depends on the availability of shelter and the possibility for concealment in the substrate (Finstad et al. 2007). Very large stones or woody debris help to prevent clogging, because they induce locally higher current velocities, and they enhance downwelling and upwelling exchanges between the surface and ground water upstream and downstream of the object (Sæterbø et al. 1998, Boulton 2007). Larger stones or blocks provide also cover for fish, which is important for example to reduce stranding risk during hydropeaking operations (Vehanen et al. 2000, Saltveit et al. 2001).



Figure 21. Groundsill made of loose material in the river Glomma near Lyngen (Hedmark district, left) and a series of small stone weirs in the river Hareidselv (Møre and Rømsdal district, right). From Sæterbø et al. (1998)

Fish stocking and planting of salmonid egg is a widely used strategy to mitigate negative environmental impacts on recruitment or to increase fish production and yield. The main species stocked are brown trout, *Salmo trutta* L., and Atlantic salmon, *Salmo salar* L. (Saltveit 1998; Fjellheim & Johnsen 2001, Johnsen et al. 2010).

Altered sediment and flow regimes in regulated rivers limit available spawning habitat for many fishes, especially salmonids. A traditional method to mitigate the loss or impairment of salmonid spawning areas, and thereby negative effects on stock recruitment is to dump spawning substrate (diameter 2-5 cm) on the river bed (Sæterbø et al. 1998, Barlaup et al. 2006). In-situ monitoring studies showed that establishing new spawning areas by addition of gravel (Fig. 22) was successful (Barlaup et al. 2008, Linnannsaari et al. 2009, Johnsen et al. 2010). However, large floods could be a major drawback, and ice processes should be considered when habitat enhancement projects are planned and carried out.

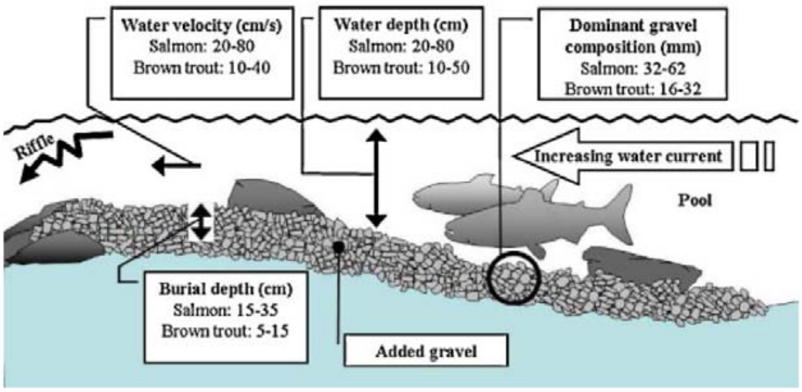

Fig. 22 : Schematic representation of a gravel addition to establish a new spawning area at an outlet of a pool. Typical characteristics of spawning areas are shown in boxes. Characteristics for brown trout is given for trout with length <30 cm. From Barlaup et al. (2008).

The hydropower industry has been strongly associated with the problem of massive *J. bulbosus* growth in regulated freshwaters in southern Norway (Fig. 23), although other factors such as climate, acid rain, liming, and nutrients also may have contributed to the expansion of this species

(Rørslett and Johansen 1996, Johansen et al. 2000, Vegge and Haraldstad 2006). The in-stream measures to handle enhanced growth of aquatic macrophytes include weir building, mechanical methods using excavators, harvesters and cutting devices, and sucking of mud and sludge to remove the macrophytes including their roots.

Figure 23: Growth of *Juncus bulbosus* in river Otra (left) and removal of this plant in river Mandalselva (right). From Vegge and Haraldstad (2006)

Measures in reservoirs

Brodtkorb (2001) suggested a suitability classification system for reservoirs where peaking regulation is planned. A suitable lake or reservoir for short-term regulation should have a large volume (giving less change in water level) and coarse bottom substrate to reduce the effect of erosion. Biologically, it was regarded as advantage when the reservoir was already heavily regulated, with an ecosystem already strongly impaired and species adapted to an unstable environment.

Pedersen and Sollibraten (2001) discussed the different erosion forces and protection measures, which may arise in the transition from traditional hydropower regulation to diurnal hydropower peaking. In addition to traditionally used materials such as rock, wood, concrete and synthetic materials, they suggested bioengineering measures to control erosion.

Hydropeaking affects the development of vegetation within the fluctuation range of the reservoir. Beside operational measures (limitation of the fluctuation range), the re-vegetation of reservoir shores with native aquatic vegetation can be supported by sediment seed banks or nearby sanctuaries from which aquatic plants can extend into the reservoir, or by amending the shore substrate by light dressing with fertilizers (Rørslett and Johansen 1996).

4.3 Example: Limitation of flow rate changes to prevent stranding

The effects of sudden and strong reductions in flow on fish have been studied in several Norwegian rivers (Hvidsten 1985, Forseth *et al*., 1996).

Saltveit et al (2001) tried to quantify the effects of rapid flow changes on juvenile Atlantic salmon (*Salmo salar*) and brown trout (*Salmo trutta*) by obtaining quantitative data for survival and mortality, aiming to produce guidelines for hydropower companies to reduce fish stranding. The river Nidelva near Trondheim was selected because earlier studies had shown that rapid and frequent reductions in flow had caused stranding of fish (Arnekleiv *et al.*, 1994). A 75 m^2 enclosure in the drawdown zone of the regulated river was stocked with a known number of wild 0+ and/or 1+ wild Atlantic salmon (*Salmo salar*) and brown trout (*Salmo trutta*). The number stranded was estimated by counting the surviving fish collected in a bag as they left the enclosure (Fig. 24). In their study, the most important factors affecting stranding rates in wild Atlantic salmon and brown trout were temperature, time of year and light conditions or time of day. The highest stranding rates were found at low water temperatures in daytime during mid-winter.

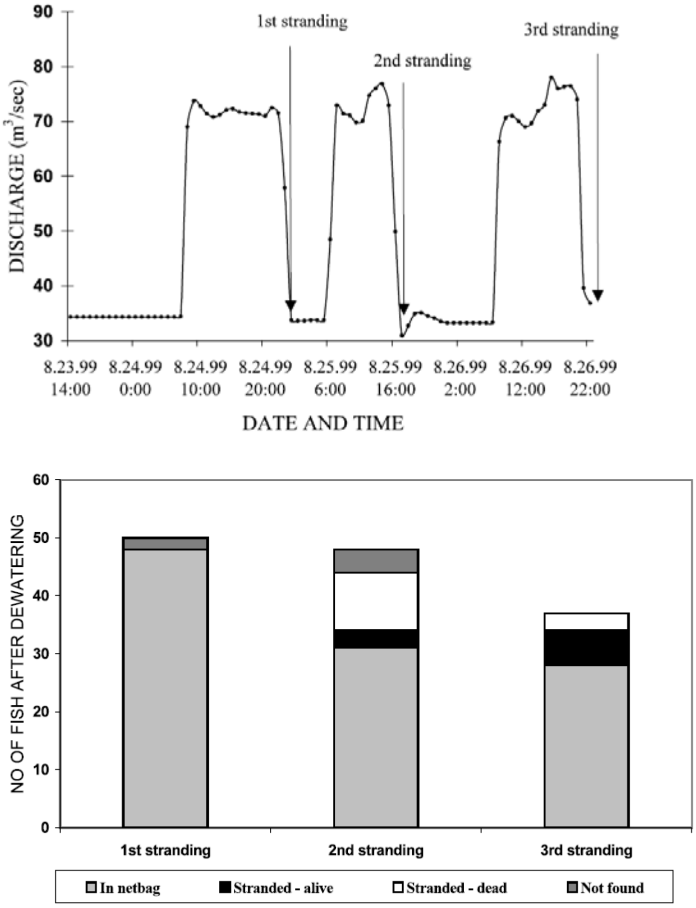

Figure 24: Number of Atlantic salmon found stranded, missing or in the net bag after repeated dewatering of the enclosure during a 3-day period of hydropeaking in August 1999. From Saltveit et al. (2001)

To provide environmental guidelines for operation of peaking hydropower plants, Halleraker et al. (2003) conducted stranding experiments with juvenile brown trout (*Salmo trutta*) in a 3.8 m wide and 19.2 m long artificial stream. They found a significant decrease in stranding of trout fry by reducing the dewatering speed from >60 cm/h to <10 cm/h. Their experiments showed a strong dependency of the stranding risk on temperature and time of the day. Cold water combined with coarse substrate, low gradient, and high current velocity gave the highest stranding incidents. They recommend dewatering in darkness at all times of year to reduce stranding of salmonids, and to use slow ramping rates <10 cm/h. For rivers dominated by coarse substrate, ultra-slow ramping rates (<10 cm/h) had to be achieved. After longer periods with stable flows, a gentle drop in discharge was recommended, which might also reduce stress and possible sub-lethal effects.

Based on such stranding investigations, some hydro power plants (e.g. Dale power plant, BKK) have introduced site-specific schemes controlling the ramping rates and times when reducing discharge or closing the power plant (Johnsen et al. 2010, Oppedal 2011).

4.4 Summary and outlook

Hydropeaking mitigation measures in Norway are similar to those described in Chapter 2.1 for other regions, however with a stronger focus on the fish species Atlantic salmon and erosion problems.

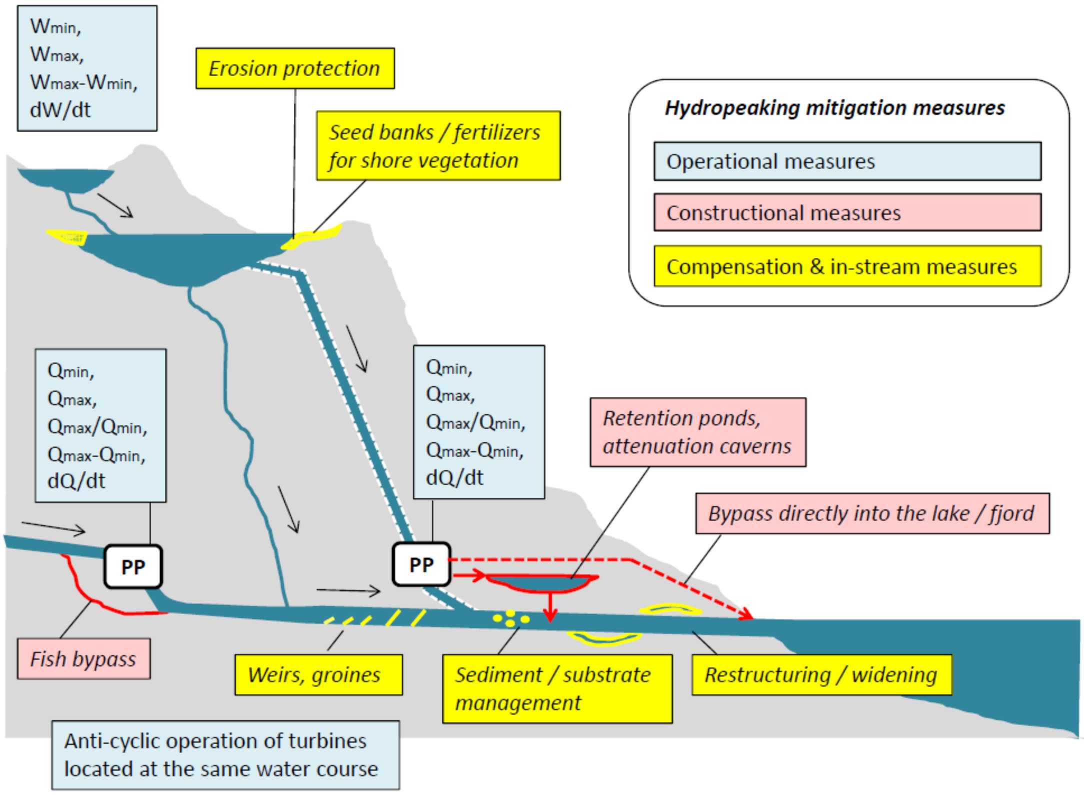

Figure 19. Scheme of hydropeaking mitigation measures that are used or may be relevant for Norwegian conditions

Figure 25 illustrates the major points according to the current state of knowledge. Practical applications for most of the mentioned measures can be found. In future, more integrated concepts are necessary. It has to be investigated whether anti-cyclic operation of turbines located at the same water course is relevant.

The operational measures include:

i. In rivers
- attenuating the magnitude of discharge peaks
- slowing down the rate of change for discharge (dQ/dt)
- limiting and increasing the minimum flows (Qmin)
- flushing flows (Qmax)
- proper choice of release type

ii. In reservoirs
- slowing down the rate of change for water level (dW/dt)
- reducing the designed fluctuation range (Wmax-Wmin)
- adjust regulation limits to prevent erosion in critical geological zones

The constructional measures related to the power plant include:

iii. In rivers
- Retention ponds or attenuation caverns
- Fish migrating pathways

iv. In reservoirs
- intakes situated in different heights
- Retention ponds or attenuation caverns

The compensation and in-stream measures include:

v. In rivers
- Building of ground sills, weirs, or river pavements
- Building of groins, or implementation of large stones
- Distribution of spawning substrate (gravel)
- Fish stocking and removal of fish barriers
- Re-meandering; opening of side-channels (possibly)
- Measures to treat enhanced or reduced growth of vegetation

vi. In reservoirs
- Erosion protection measures
- Support measures for re-vegetation of the reservoir shores, such as seed-banks or use of fertilizers

5 List (non exhaustive) of mitigation measures over the world

Scientific knowledge about solutions to mitigate hydropeaking effects is developing and measures are taken in a lot of countries to match hydropower production with environmental requirements. Knowledge is presented in technical reports and scientific papers but it often concerns solutions to a specific problem in a specific site/river. Summarizing and analyzing a broad selection of examples will provide an overview on the current state of knowledge in the mitigation domain.

Literature related to mitigation measures from all over the world has been reviewed and sum-up in a table (**Appendices**). The summary aims at providing an overview of mitigation measures taken or proposed in several countries to attenuate negative impacts of hydropeaking in rivers. Giving the goal of measures related to changes in hydraulic regime as well as the expected biological improvements, and describing the achievement of measures (limitations, monitoring), the summary presents the main aspects of each mitigation solutions so that measures can be easily compared. The list of examples can serve as a basis to propose mitigation solutions against ecological issues encountered in hydropeaked rivers. However, every river is unique and all measures have to be modified and adapted to answer positively to local problems.

Relevant information about mitigation was found in scientific papers, but also in technical reports from hydropower plant operators and in studies conducted by national or local environmental agencies. The reviewed documents mainly refer to mitigation measures taken in European countries with hydropower production (Switzerland, Austria, France and Norway), but also in North America. Thus examples mentioned in the summary range from narrow and steep rivers in the Alps to wide and low slope rivers in the USA. About 40 different mitigation measures are listed in the table. The same measure is sometimes taken in different sites/rivers.

In the table (**Appendices**), mitigation measures are sorted in 8 different targets:

- Avoidance of variations in flow and water level;
- Reduction of magnitude of flow and water level variations;
- Attenuation of flow and water level increases and decreases;
- Seasonal improvement: Reduction of magnitude and attenuation of variations in flow and water level;
- Reduction/Avoidance of temperature variations;
- Minimization of area affected by wetting and drying, Expansion of constantly inundated area;
- Reduction the propagation of hydropeaking waves;
- Improvement of river quality and river restoration.

The mitigation measure itself (e.g. increase of minimum flow, building of shelters), its type (constructional, operational, in-stream) and its realization (e.g. recommendation of discharge value, slow down in shutting-down of turbines, introduction of substrates) is described. The expected environmental improvements and monitoring are also specified for each example. Finally the specific reference is mentioned so that additional and detailed information can be found in the related documents.

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Appendix: Table of mitigation measures

SINTEF

ID	Aim	Measure	Type	Realization	Environmental improvements expected	Application examples	Monitoring	Literature source
1	Avoidance of variations in flow and water level	Separate discharge of (parts of) turbined water	C	Tunnel/channel from hydropower plant directly to a lake or a larger stream; divertion into flood plain	Alternative for different fish species during the first life stages	6 hydropower plants release tailwaters in tunnels which go directly to Lake Maggiore (Canton of Ticino, CH)	-	Meile et al. (2005)
						Discussed for Innertkirchen I and II power plants, in Hasliaare River (CH)	-	Limnex (2004)
						Trun-Ferrera (CH)	-	Baumann & Klaus (2003)
2			C	Parallel channel/Bypass section for fish	Alternative for different fish species during the first life stages	Kreuzbergmaut power plant, Salz River (A)	Study of 15 fish species: Fishes have colonized the artificial by-pass and use it. Same species than in the original stream found in the channel. Still deficit dur to sedimentation problems.	Petz-Glechner & Petz (2002)
3		Protect well preserved (natural) streams from hydropeaking	A	Reduce the number of streams regulated	Concentration of consequences on few catchments/streams	USA	Project in process of planning	Baumann & Klaus (2003)
4			C	Release the water in a less influenced part of the river	Protect a specific area	Tailwater released 25 kom downstream: Inn River (CH),	Project in process of planning. Achieved by 2013	LCH (2006)
5		Stop the hydropower production	O	Close-down the hydropower plant	Maintain existing conditions in the river	Discussed for Innertkirchen I and II power plants, in Hasliaare River (CH)	-	Limnex (2004)
6	Reduction of magnitude of flow and water level variations	Increase of minimum flow	O	Additional release from storage/weir/dam	*Not specified*	Le Châtelot dam, Doubs River (border CH. and F.)	Project in process of planning	Baumann & Klaus (2003)
7			O	Increase of minimum discharge released from the turbines Increase of minimum discharge released from the turbines	Improve habitat availability and quality; trout population	7 sites :2 in the Alps, 3 in the Pyrenees, 2 in the Massif Central region (France) (from 1/40 to 1/10 of Mean Annual Flow)	Increase in the potential habitat; slightly increase of brown trout population	Sabaton et al. (2008)
					Attenuation of peaking effects for aquatic habitats	Hauterive HP, Sarine River (CH), Verbois HP, Rhone River (CH), Islas HP, Inn River (CH), Linthal HP , Linth River (CH), Kubel HP, Saint-Gall canton(CH), Le Chalet, L'Orbe River (CH), Plan-Dessous (CH)	In most cases: only low reduction of the maximum difference between peak and min. discharge	Limnex (2001), Baumann & Klaus (2003)
					Avoid drying of spawning grounds; Higher availability of salmonides spawning habitats; Increase of smolt production.	Downstream Argentat, Dordogne River (F):10 to 35 m3/s (15^{th} nov. - 15^{th} june)	Number of dewatered spawning grounds decreased	Epidor (2002), Epidor (2009), Moor (2009)
						Downstream Hautefage dam, Maronne River (F): 0.5 to 1 m3/s; Requirement of seasonal min flow: 3 m3/s (15^{th} nov-15^{th} june)		

ID	Aim	Measure	Type	Realization	Environmental improvements expected	Application examples	Monitoring	Literature source
	Reduction of magnitude of flow and water level variations	Increase of minimum flow				Downstream Brugales HP, Cere River (F) 1 to 2 m3/s Requirement of seasonnal min flow: 3 m3/s (15th nov.- 15th june)		
8			O	Definition of environmental minimum flow	Avoid dewatering of aquatic habitats	Gordon River, Tasmania (Australia) 10 m3/s (1st dec-31th May); 20 m3/s (1stJune-30th Nov)	Maintain of aquatic habitat. Increase in macro-invertebrates abundance and diversity. Low number of fish made the assessment of measures difficult	HydroTasmania (2010)
9		Decrease of maximum flow	O	Decrease of maximum flow released from the turbines	Avoid pool-trapping of juvenile salmonids fish	Downstream Argentat, Dordogne River (F):: 340 to 190 m3/s (15th march - 15th June)	Number of pool-trapped juveniles decreased	Epidor (2002), Epidor (2009), Cazeneuve et al. (2009)
						Downstream Hautefage dam, Maronne River (F):35 m3/s (15th march - 15th June)		
					Not specified	Langenegg (CH)	*Not specified*	Baumann & Klaus (2003)
10		Increase of minimum flow and decrease of maximum flow	C	Building of an attenuation reservoir	Attenuate peaking fluctuations, insure a higher minimum flow.	Walgauwerk (A) (www.illwerke.at) Ramsach (A) Hintermuhr (A)	*Not specified*	Baumann & Klaus (2003) Meile (2005)
					Higher minimum flow in combination with lower peak flows	Linthal (CH), Alberschwende (CH), Walgauwerk (CH), Ramsach (CH), Arnsteg (CH), Hintermuhr (CH)	Less (but still ecological important) peaking effects.	Limnex (2001), Baumann & Klaus(2003), Limnex (2004), Meile (2005)
11			O	Anti-cyclic operation of hydropower plants located along the same watercourse (time-delayed peak-releases at other HP)	Reduction of all peaking effects for fish habitat and reproduction	Reichenau (A)	In process of planning	Eberstaller (2001)
					Not specified	Wald (A)	Project in process of planning	Baumann & Klaus (2003),
12		Limitation of magnitude ratio Qmax/Qmin	O	Limit the magnitudes of flow released by the turbines	To maintain ecological functions of the river	Kreuzbergmaut power plant, Salzach River (A) Qmax/Qmin= 3 : 1	*Not specified*	Limnex (2004)
					To maintain ecological functions of the river	Austria; recommendations for the realization of the EU Water directive. Qmax/Qmin =5 : 1 for small to middle-sized rivers (basin < 2500 km^2)	*Not specified*	LCH 2006
13			C and O	Attenuation reservoirs / storage capacities and mangement of flow	To maintain ecological functions of the river	Estimation of storage volume needed in six Swiss rivers (Aare, Rhone, Rhine, Reuss, Inn, Ticino) guarantee a ratio Q_{max}/Q_{min} = 5:1 for the downstream river	- (Suggestions)	LCH 2006
14			C and O	2 re-regulating reservoirs were constructed; Introduction of a pre-peaking phase	Allow anticipation of peaking by adapting behavior of fauna; Maintain a higher minimum flow	Bregenzerach River (A) Qmax/Qmin modified to 60:20:3	Benthic biomass increased from 15 to 60% ; fish biomass did not	Parasiewicz et al. (1998)

ID	Aim	Measure	Type	Realization	Environmental improvements expected	Application examples	Monitoring	Literature source
15	Attenuation of flow and water level increases and decreases	Reduction of rates of flow decrease	O	Maximum rate of flow decrease during slow-down/shut-down of turbines	Avoid juvenile salmonid fish stranding at decreasing flow phases.	Argentat, Dordogne River (F), 33 m3/s/h for Q > 80 m3/s; 10 cm/s/h for Q < 80 m3/s (15^{th} mars- 15^{th} June)	Number of stranded juvenile fish decreased	Epidor (2002), Epidor (2009)
					Avoid juvenile salmonid fish stranding at decreasing flow phases.	Downstream Hautefage dam, Maronne River (F): 5m3/s/h (15^{th} mars- 15^{th} June)	Number of stranded juvenile fish decreased	Epidor (2002), Epidor (2009)
					Avoid juvenile salmonid fish stranding at decreasing flow phases.	Basteyroux station, Maronne River (F) :10 m3/s/h (15^{th} mars- 30^{th} Sept)	Number of stranded juvenile fish decreased	Moor (2009)
					Attenuation of peaking effects, avoid negative effects for river habitats	Plan-Dessous, Aubonne River (CH), Le Châtelot (CH)	No data for monitoring	Limnex (2001)
					Avoid stranding of fishes	Experiments in Vikja River, in Bævra River, in Barduelva River, and in Tokkeåi River (Norway)	Shutting-down time still over the ecological requirements. Less fish stranded found after the experiments.	Statkraft. Produksjonsplan-legging og vassdragsmanøvre-ring. Internal document.
16		Reduction of water level decrease	O	Maximum rate of water level decrease during slow-down/shut-down of turbines	Avoid dewatering of perch and pike spawning grounds. Ensure reproduction of these species.	Carennac, confluence Cère and Dordogne Rivers (F): 50 cm (March-15^{th} June)	Number of stranded juvenile fish decreased	Epidor (2009)
17		Reduction of rates of flow and water level increase/decrease	O	Slower or step-wise reduction of flow released from the turbines	Attenuation of negative peaking effects	Le Châtelot (CH), Kubel (CH), Plan-Dessous (CH)	Effect needs to be investigated.	Limnex (2001); Baumann & Klaus (2003)
18			O	Increase of turbines start-up time, locally combined with other measures	Avoid stranding of fishes	Verbois (CH), Islas (CH), Albertschwende (CH)	No enhancement observed on aquatic life.	Limnex (2001), Baumann & Klaus (2003) Meile (2005)
19			C	Attenuation reservoir	-	Walgauwerk (A) Ramsach (A), Hintermuhr (A)	-	Baumann & Klaus (2003)
20	Seasonal improvement in regard flow and water level variations	Modify flow requirements (magnitude, ratio, rate of variation) according biological phase of fishes	O	Release more water during spawning periods	Improve river and fish habitats	Islas HP, Inn River (CH)	-	Limnex (2001)
21		Induced flood during minimum discharge periods	O	Successive 24h-release of water in the regulated river	Encourage return migration of adult Atlantic salmon	Gudbrandsdalslågen River (Norway)	Brown trout managed to pass the tunnel issuing (with rapidly flowing water) and enter the regulated stretch	Brown trout managed to pass the tunnel issuing (with rapidly flowing water) and enter the regulated stretch
22		Avoid attraction of fish to the water diverted through the power station	O	stop of the hydropower plant during the return migration	Encourage return migration of adult Atlantic salmon	Suldalslågen River (Norway)	Slightly attraction to the freshwater release, no significant delay in migration	Thorstad et al. (2003)
23		Develop a flexible environmental flow regime	O	Design of a variable environmental flow regime folowing the natural flows variations, based on 3 levels (low, medium, high flow)	Meet flow needs of the Atlantic salmon for spawning, hatching, swim-up, rearing of juveniles, outmigration of smolts, adult migration, recreational salmon fishing	Daleelva River (Norway)	No monitoring	Alfredsen et al. (2011)

ID	Aim	Measure	Type	Realization	Environmental improvements expected	Application examples	Monitoring	Literature source
24	Reduction/ Avoidance of temperature variations	Provide habitats with good temperature conditions	C-is	Link main river to oxbow lakes and smaller side channels	Provide shelter and retreat possibilities for river organisms (allowing them to escape from the main stream when temperature conditions are unfavourable)	Rhone proposed by Meier et al. (2004)	No monitoring	Meile (2005)
25		Attenuation of temperature fluctuations	C-is	River widening	Creation of still-water zones that allow temperature adjustment	Rhone proposed by Meier et al. (2004)		Meile (2005)
26			C	Attenuation reservoir	Smoothen temperature fluctuations	Rhone proposed by Meier et al. (2004)		Meile (2005)
27		Withdraw and release of water with temperature properties that match the ecological needs	C	Multi-level intake structure to select withdrawal	Increase summer water temperature downstream the dam for trout	Flaming Gorge Dam, Green River (USA)	Increase in spring-summer temperature towards unregulated conditions but no increase in invertebrates richness as expected (Pb: still damaging sedimentation processes	Olden and Naiman (2009)
					Improve downstream temperatures for coldwater salmonids (release warmer surface water in the wainter/spring and colder deeper waters in the summer/autumn)	Shasta Dam, Sacramento River (USA)	-	Olden and Naiman (2009)
				Multi-level intake struture to select withdrawal Numerical simulation	Increase spring/early summer water temperature downstream post-spawning period for cod	Hume Dam, Murray River (Australia)	Predicted increase in female cod population abundance (modeling)	Sherman et al. (2007)
28	Minimization of area affected by wetting and drying; Expansion of constantly inundated area	Restructuring/redesign of stream channel by various in-stream structures; restoration of river sections	C-is	Construction of weirs (wood, concrete, moraine material)	Reduce water velocities; increase wetted area and water volume; increase fish habitat diversity; Improve fish recruitment; reduce erosion	Ekso River, Norway Nea River (Norway)	Benthos biomass increased strongly. Trout colonized the weir basin. Increased fish density Potential negative effects need to be evaluated: increased sedimentation, fish community changes, migration barrier, macrophyte growth	Brittain (2001)
29		River widening	C-is	River widened by 20m, Creation of a new anabranch, creation of wetland waterbodies	Increase in juvenile fish biomass and amphibians	Almach site, upper Drau River (A)	amphibians diversity increased; no monitoring for fish yet	http://www.life-drau.at
30	Reduction the propagation of hydropeaking waves	Find out the best shape for the riverbank and reduce the reflection of waves	C-is	Reshape the riverbank	-	Rhone-Thur project	Only laboratory simulation	EPFL-LCH, 2006

ID	Aim	Measure	Type	Realization	Environmental improvements expected	Application examples	Monitoring	Literature source
31	Improvement of river quality and river restauration	Development of spawning ground	C-is	Gravel (size: 0.6 to 15 cm) delivered to the river bed with a plastic pipe and spread by hand	Chinook salmon spawning habitat created (160 m²)	Campbell River (Canada)	No monitoring	Anderson (2004)
32			C-is	Provide artificially alluvium in the bed river to create areas with appropriate size of sediments. Numerical modelling set-up to define effect hydraulic	Create salmonids spawning grounds to ensure reproduction	Upstream Argentat Dam, Dorodgne River (F)	Experimental phase	Epidor (2002)
33		Building of shelters for fishes and/or invertebrates	C-is	Lateral embayment at a channel bank as a fish refuge (2 x 1.2 m^2)	Prevent effects of high velocities during hydropeaking episodes by creating a fish refuge.	Maigrauge dam, Fribourg (CH)	In-stream test of shelter with different configurations. Basic refuge configurations with low exchange with the main flow are not attractive for fish. Triangle form for shelter is efficient.	Ribi et al.(2010)
34			C-is	Deposit of rocks [from 1 to 0,5 m^3] every 10m along 100-200m linear stretches	Avoid the impact of hydropeaking [fishes, benthos swept away by the stream] in stretches, where there are steep banks.	downstream Hautefage Dam, Maronne River (F), downstream Trignac Dam, Vezere River (F)	-	Epidor (2002)
35			C-is	Plantation of riparian trees such as black alder and willow	Provide nutrient and sediment retention. Create in-stream cover habitat. Restore same habitat conditions as in upstream reference sites.	New Zeeland	Macroinvertebrates community became more similar to ones in reference sites. Increase in fish biomass that use pool shelter	Jowett et al. (2009)
36		Diversify physical habitat for fishes and/or invertebrates	C-is	5 in-stream structure types: 1.weirs, 2.deflectors, 3.cover structures, 4.boulder placements, 5.large wood debris	Diversifying physical habitat; increase biomass and salmonids abundance	211 stream projects (USA & Canada): meta-analysis	Increase in pool area, depth, LWD recruitment and overhead cover, decrease in riffle area. - 73% of restoration projects resulted in an increase in salmonid density. - 87% of restoration projects resulted in an increase in salmonid biomass. All stream structure types had similar impacts on restoration effectiveness. Larger fish benefited more from restoration efforts.	Whiteway et al. (2010)
			C-is	artificial riffles (piles of coarse mineral substrata); flow deflectors (struture to narrow the channel and create faster flow area)	Diversifying river habitat (increase heterogeneity in flow velocity and depth)	13 lowland rivers, central and eastern Britain (Great Britain)	Little evidence of significant increase in fish abondance, specie richness, diversity, equitability. Fish species richness and diversity responded positively to increased flow velocity	Pretty et al. (2003)

ID	Aim	Measure	Type	Realization	Environmental improvements expected	Application examples	Monitoring	Literature source
37	Improvement of river quality and river restauration	Create a multi-purpose project (combination of different measures)	C-is	Widening of the river (flood protection, navigation); building of attenuation reservoir; artificial river ladder; operational regime management	Ensure vertical and lateral connectivity; maximize fish habitat diversity; Increase zoobenthos richness	Upper Swiss Rhone River within the framework of the SYNERGIE project: modeling of with optimization tool developped by Pellaud (2006)	Optimization model built for multi-purpose project. This type of project is efficient only if constructional measures are combined with operational mitigation measures (flow mangement)	Pellaud (2006)
38		Create artificial high flow for river renaturation	O	Release a high amount of water from the dams during a short period.	Re-establishment of formerly eroded sand banks; cleaning of rapids from wooden debris and sediment deposits; increase of suspended sediment concentrations (= better conditions for native fish species)	Colorado River	Successful cleaning/reactivation of rapids. Expectations were not fully met for the sand banks and aquatic life.	Limnex (2004)
39		Reduction of the infiltration of fine sediments due to hydropeaking	O	Cleaning up operation for hydropower plants	Renaturation of the riverines	[10]Switzerland	In process of planning	[10]GschV (2010)

"O" : Operational mitigation measures
"C" : Constructional mitigation measures
"C-is" : In-stream renovation measures
HP : Hydropower plant
CH : Swizterland
F : France
A :Austria

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